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LAKE ERIE INTERNATIONAL JETPORT MODEL FEASIBILITY INVESTIGATION

Report 17-9

RESULTS OF NUMERICAL THREE-DIMENSIONAL WIND-DRIVEN CIRCULATION ANALYSIS FOR THERMALLY STRATIFIED LAKE CONDITIONS

by

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January 1978

Report 9 of a Series

Prepared for Lake Erie Regional Transportation Authority
Cleveland, Ohio 44113

under Task 17 of LERTA Third-Phase
Airport Feasibility Study

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The wind-driven circulation for thermally stratified lake conditions in a 16-mile by 16-mile nearshore region offshore Cleveland, Ohio, is studied for existing conditions and conditions as modified by a proposed jetport island. A steady-state 12 mph west wind, which produced maximum jetport effects in a previous WES study of the steady-state wind-driven circulation for well-mixed lake conditions in the nearshore region offshore Cleveland, Ohio, was chosen as the wind field for the model study. In a previous

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20. ABSTRACT (Continued)

contracted study[1] by WES, a 12 mph south wind, which represents the modal wind speed and most frequently occurring wind direction for the months of July, August, and September, was used in studying the proposed jetport effects on wind-driven circulation for summer lake conditions. For the 12 mph west wind field, results for the horizontal velocity and temperature regimes with and without a jetport are presented. Included in the results are plots of horizontal velocity vectors and isotherm contours with and without a jetport and contours of differences in horizontal velocity and temperature regimes in the nearshore region due to jetport. Based on the results of this study and a previous WES contracted study[1] using a 12 mph south windfield, the effects of a proposed jetport island on wind-driven circulation for thermally stratified lake conditions are that (a) major island influences of engineering interest are contained within 3 to 5 miles of the island, (b) velocity changes of 0.25 ft/sec extend to the shore in the immediate vicinity of Cleveland, Ohio, while temperature changes of 0.5°F extend within 1 mile of the shoreline, and (c) maximum changes in velocity and temperature (1.5 fps and 15°F) regimes occur within 2 miles of the island in strong upwelling and downwelling regions along the perimeter of the island.

PREFACE

The numerical, three-dimensional, wind-driven circulation study of the effect of a proposed offshore airport on the thermally stratified lake conditions in Lake Erie near Cleveland, Ohio, was sponsored by the Lake Erie Regional Transportation Authority (LERTA), Cleveland, Ohio, as a part of the model feasibility investigation being conducted at the U. S. Army Engineer Waterways Experiment Station (WES). The WES investigation, Task 17 of the LERTA investigation, is a portion of the third-phase airport feasibility study undertaken by LERTA to evaluate airport sites, one of which is in Lake Erie near Cleveland.

This report and the numerical analyses were prepared and conducted by Dr. Donald L. Durham of the Wave Dynamics Division (WDD), WES, and Dr. Donald C. Raney, who was working with WDD while on loan from AME Department, University of Alabama through the Intergovernmental Personnel Exchange Program. This study was conducted under the general supervision of Dr. R. W. Whalin, Chief of the Wave Dynamics Division, and Mr. H. B. Simmons, Chief of the Hydraulics Laboratory. Assisting in data reduction for this study were Mr. K. A. Turner, Mrs. Judy Jones, and Mr. R. E. Ankeny, WDD. The authors express their appreciation to Dr. John Paul, who is working with Large Lakes Research Station, U. S. Environmental Protection Agency while employed with Case-Western Research University, for his assistance in supplying revised computer codes and his suggestions for code conversion.

Directors of WES during the conduct of this investigation and the preparation and publication of this report was COL G. H. Hilt, CE, and COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	2.54	centimetres
inches per second	2.54	centimetres per second
inches^2 per second	6.4516	centimetres^2 per second
pounds	4.448×10^5	dynes
feet	0.3048	metres
feet per second	0.3048	metres per second
miles	1.6093	kilometres per hour
miles per hour	1.6093	kilometres per hour
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*

* To obtain Celsius (C) temperature reading from Fahrenheit (F) reading use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

LAKE ERIE INTERNATIONAL JETPORT MODEL FEASIBILITY INVESTIGATION

RESULTS OF NUMERICAL, THREE-DIMENSIONAL, WIND-DRIVEN CIRCULATION ANALYSIS FOR THERMALLY STRATIFIED LAKE CONDITIONS

PART I: INTRODUCTION

1. The Lake Erie Regional Transportational Authority (LERTA) is conducting a feasibility and site selection study for a major hub airport in the Cleveland Service area. One of the possible sites being evaluated is an offshore site in Lake Erie near Cleveland, Ohio. As a part of the feasibility analysis of an offshore site, the U. S. Army Engineer Waterways Experiment Station (WES) conducted a model feasibility investigation and is performing numerical model studies. The results of these efforts are being published in a series of reports under the general title "Lake Erie International Jetport Model Feasibility Investigation." This miscellaneous paper presents preliminary results of the numerical simulation analyses of wind-driven circulation for thermally stratified lake conditions in Lake Erie. These data are results from WES' converting and revising a set of computer programs originally developed[1] at Case-Western Reserve University and WES running a 12-mph wind from a west direction. This steady-state wind field represents the modal wind speed[2] during the summer months (June-August) and the direction of the steady-state wind field possessing the maximum pertrubation produced by the proposed jetport island on the steady-state, wind-driven circulation[3] for well-mixed lake conditions in Lake Erie.

PART II: HYDRODYNAMIC MODEL

Mathematical Formulation

2. As part of WES numerical model feasibility study,[4] the scheme which is used in this investigation was selected from a limited number of models which calculate wind-driven circulation for thermally stratified lake conditions in large lakes. The selected model was developed and initially applied[1] in testing the effects of a proposed jetport island offshore of Cleveland on the hydrodynamics of the nearshore region containing the island. Details of this numerical model can be found in References 1, 4, and 5. An abbreviated statement of the hydrodynamic model and assumptions are presented here in summary form.

3. Basic equations for the numerical model are derived from the time-dependent, three-dimensional equations of motion for a viscous, heat-conducting fluid. Figure 1 is a schematic of the model geometry. In deriving the model, the following assumptions are made:

a. Pressure is assumed to vary hydrostatically; therefore,

$$\frac{\partial P}{\partial z} = \rho g.$$

b. The rigid-lid approximation is made, i.e., $w(z=0)=0$.

c. The Boussinesq approximation which assumes that density variations are small and can be neglected except in the gravity term is made.

d. Heat sources and/or sinks in the fluid are neglected.

e. Eddy coefficients are used to account for the turbulent and molecular diffusion effects in both the momentum and energy equations. The horizontal coefficient is assumed to be constant but the vertical coefficient is assumed to be dependent on the local vertical temperature gradient.

f. Variations in bottom topography are assumed to be gradual.

4. This numerical model allows for variations in the depth of the lake basin. It uses a nonconformal mapping procedure to stretch the vertical coordinate with respect to the local depth $h(x,y)$. The basic hydrodynamic equations are transformed according to

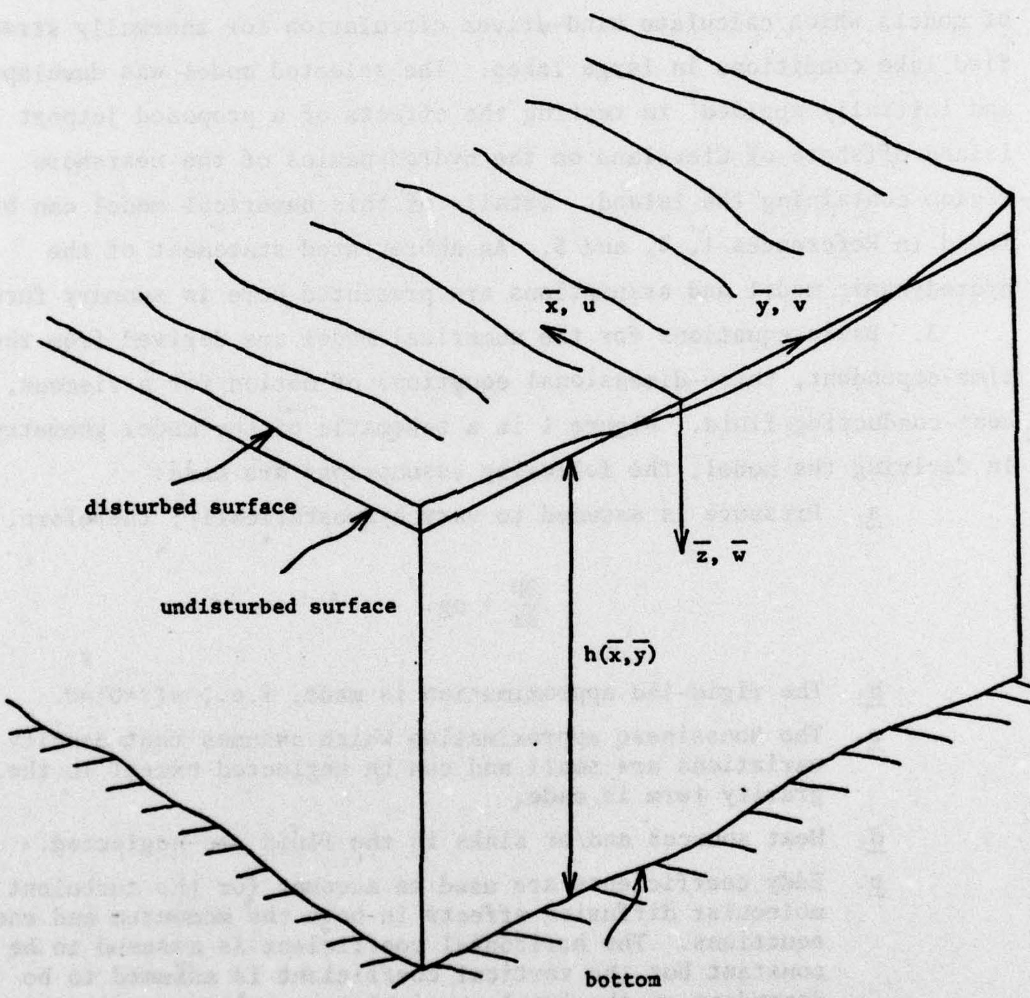


Figure 1. Geometry of hydrodynamic model

$$x \leftrightarrow x,$$

$$y \leftrightarrow y,$$

$$\sigma \leftrightarrow z/h(x,y).$$

The equations to be solved are more complicated looking because of the appearance of the depth in the equation, but they are solved for a basin of constant depth in the transformed system which greatly reduces the programming complexities of the model and makes the inclusion of depth variations simpler. A reduced form of the transformed diffusion terms are used by assuming the terms containing derivatives of the depth are neglected with respect to those terms containing only the depth. This approximation is used in meteorological problems when topographic variations are included (Refs. 6 and 7). The bottom topography $h(x,y)$ in the nearshore region of Lake Erie around Cleveland, Ohio, were obtained from Lake Survey Center charts of Lake Erie. An outline of the procedure with which these values were read from charts, interpolated and smoothed is given in Reference 8.

5. The resulting system of transformed equations, in non-dimensional form, are the following:

$$\frac{1}{h}\frac{\partial(hu)}{\partial x} + \frac{1}{h}\frac{\partial(hv)}{\partial y} + \frac{\partial\Omega}{\partial\sigma} = 0,$$

$$\frac{\partial u}{\partial t} + Re\left[\frac{1}{h}\frac{\partial(hu^2)}{\partial x} + \frac{1}{h}\frac{\partial(huv)}{\partial y} + \frac{\partial\Omega u}{\partial\sigma}\right] + Rov = -\frac{\partial P}{\partial x} + \frac{1}{h}\left[\frac{1}{h}\frac{\partial}{\partial x}\left(h\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(h\frac{\partial u}{\partial y}\right)\right]$$

$$-\frac{Re}{Fr^2}\left[h\int_0^\sigma \frac{\partial\Delta\rho}{\partial x}d\sigma + \frac{\partial h}{\partial x}\left(\int_0^\sigma \Delta\rho d\sigma - \sigma\Delta\rho\right)\right] + \left(\frac{b_0}{h_0}\right)^2 \frac{1}{h^2}\frac{\partial}{\partial\sigma}\left(\gamma\frac{\partial u}{\partial\sigma}\right),$$

$$\frac{\partial v}{\partial t} + Re\left[\frac{1}{h}\frac{\partial(huv)}{\partial x} + \frac{1}{h}\frac{\partial(hv^2)}{\partial y} + \frac{\partial\Omega v}{\partial\sigma}\right] - Rou = -\frac{\partial P}{\partial y} + \frac{1}{h}\left[\frac{\partial}{\partial x}\left(h\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(h\frac{\partial v}{\partial y}\right)\right]$$

$$-\frac{Re}{Fr^2}\left[h\int_0^\sigma \frac{\partial\Delta\rho}{\partial y}d\sigma + \frac{\partial h}{\partial y}\left(\int_0^\sigma \Delta\rho d\sigma - \sigma\Delta\rho\right)\right] + \left(\frac{b_0}{h_0}\right)^2 \frac{1}{h^2}\frac{\partial}{\partial\sigma}\left(\gamma\frac{\partial v}{\partial\sigma}\right).$$

$$\Pr\left[\frac{\partial \Delta T}{\partial t} + Re\left[\frac{1}{h}\frac{\partial(hu\Delta T)}{\partial x} + \frac{1}{h}\frac{\partial(hv\Delta T)}{\partial y} + \frac{\partial \Omega \Delta T}{\partial \sigma}\right] = \frac{1}{h}\left[\frac{\partial}{\partial x}\left(h\frac{\partial \Delta T}{\partial y}\right) + \frac{\partial}{\partial y}\left(h\frac{\partial \Delta T}{\partial y}\right)\right]\right.$$

$$+ \left(\frac{b_o}{h_o}\right)^2 \frac{1}{h^2}\frac{\partial}{\partial \sigma}\left(\beta\frac{\partial \Delta T}{\partial \sigma}\right),$$

$$\frac{1}{h}\frac{\partial P}{\partial \sigma} = \frac{Re}{Fr^2}(1 + \Delta\rho),$$

$$\Delta\rho = f(\Delta T),$$

$$\sigma = z/h(x,y),$$

$$\Omega = \frac{1}{h}\left[w - \sigma\left(u\frac{\partial h}{\partial x} + v\frac{\partial h}{\partial y}\right)\right] = \frac{d\sigma}{dt},$$

where:

$u = \frac{\bar{u}}{u_o}$, $v = \frac{\bar{v}}{u_o}$,

$w = \frac{\bar{w} b_o}{u_o h_o}$, $x = \frac{\bar{x}}{b_o}$,

$y = \frac{\bar{y}}{b_o}$, $z = \frac{\bar{z}}{h_o}$,

$P = \frac{\bar{P} Re}{\rho_o g h_o Fr^2}$, $\Delta\rho = \frac{\bar{\rho} - \rho_o}{\rho_o}$,

$\Delta T = \frac{\bar{T} - T_E}{T_E}$, $t = \frac{\bar{t} A_H}{b_o^2}$,

$\gamma = \frac{A_V}{A_H}$, $\beta = \frac{B_V}{B_H}$,

$Ro = \frac{k b_o^2}{A_H}$, $Fr = \frac{u_o}{\sqrt{g h_o}}$,

$Pr = \frac{A_H}{B_H}$, $Re = \frac{u_o b_o}{A_H}$,

$\rho_o = \bar{\rho}(T_E)$ and

u_o = reference velocity,

b_o = horizontal reference length,

h_o = vertical reference length,

A_H = horizontal eddy viscosity,

A_V = vertical eddy viscosity,

B_H = horizontal eddy diffusivity,

B_V = vertical eddy diffusivity,

T_E = equilibrium temperature which is temperature at the surface for which there is no heat transfer.

k = Coriolis parameter,

$f(\Delta T)$ = equation of state and

$(\bar{\ })$ = refers to dimensional quantity.

6. The Poisson equation for pressure, which contains the rigid-lid condition, is derived by taking the divergence of the vertically integrated horizontal momentum equations and using the vertically integrated continuity and hydrostatic pressure equations. The Poisson equation is

$$\frac{\partial}{\partial x} h \frac{\partial P_s}{\partial x} + \frac{\partial}{\partial y} h \frac{\partial P_s}{\partial y} = -h \frac{\partial}{\partial t} (\Omega(\sigma=o))$$

$$+ (\frac{b_o}{h_o})^2 \frac{\partial}{\partial x} (\frac{1}{h} \gamma \frac{\partial u}{\partial \sigma})_{\sigma=1} - \frac{1}{h} \gamma \frac{\partial u}{\partial \sigma})_{\sigma=0})$$

$$+ (\frac{b_o}{h_o})^2 \frac{\partial}{\partial y} (\frac{1}{h} \gamma \frac{\partial v}{\partial \sigma})_{\sigma=1} - \frac{1}{h} \gamma \frac{\partial v}{\partial \sigma})_{\sigma=0})$$

$$- \frac{\partial}{\partial x} h \int_0^1 [Re(\frac{1}{h} \frac{\partial hu^2}{\partial x} + \frac{1}{h} \frac{\partial huv}{\partial y} + \frac{\partial \Omega u}{\partial \sigma}) + Rov - \frac{1}{h} \frac{\partial}{\partial x} h \frac{\partial u}{\partial x}$$

$$- \frac{1}{h} \frac{\partial}{\partial y} h \frac{\partial u}{\partial y} + \frac{Re}{Fr^2} (\frac{\partial}{\partial x} h \int_o^\sigma \Delta\rho d\sigma - \sigma \frac{\partial h}{\partial x} \Delta\rho)] d\sigma$$

$$- \frac{\partial}{\partial y} h \int_o^1 [Re(\frac{1}{h} \frac{\partial huv}{\partial x} + \frac{1}{h} \frac{\partial hv^2}{\partial y} + \frac{\partial \Omega v}{\partial \sigma}) - Rou - \frac{1}{h} \frac{\partial}{\partial x} h \frac{\partial v}{\partial x}$$

$$- \frac{1}{h} \frac{\partial}{\partial y} h \frac{\partial v}{\partial y} + \frac{Re}{Fr^2} (\frac{\partial}{\partial y} h \int_o^\sigma \Delta\rho d\sigma - \sigma \frac{\partial h}{\partial y} \Delta\rho)] d\sigma \quad .$$

where P_s is the integration constant resulting from the vertical integration of the hydrostatic pressure equation and is the surface pressure i.e., the pressure at the surface $z = 0$.

7. The following boundary conditions are used with the above system of equations.

River outflow

$$u = g_1(y,z)$$
$$v = g_2(y,z)$$
$$\Delta T = g_3(y,z)$$

Shore

$$u = 0$$
$$v = 0$$
$$\frac{\partial \Delta T}{\partial n} = 0$$

Bottom

$$u = 0$$
$$v = 0$$
$$w = 0$$
$$\frac{\partial \Delta T}{\partial z} = 0$$

Surface

$$\frac{\partial u}{\partial z} = twx$$
$$\frac{\partial v}{\partial z} = twy$$
$$\frac{\partial \Delta T}{\partial z} = K\Delta T$$
$$w = 0$$

Other Boundary

either

$$\frac{\partial u}{\partial n} = 0 \quad \text{or} \quad u = f_1$$
$$\frac{\partial v}{\partial y} = 0 \qquad v = f_2$$
$$\frac{\partial \Delta T}{\partial n} = 0 \qquad \Delta T = f_3$$

Pressure Conditions

$$\frac{\partial P}{\partial n} = \text{integrated x or y momentum equation,}$$

specify pressure level at one point.

The functional forms g_1, g_2, and g_3 are the specified velocity and temperature profiles across the river outfall. Boundary conditions at the outer x and y boundaries are either that the normal derivatives of the velocity and temperature are zero, or that the velocity and temperature are specified (f_1, f_2, f_3).

Numerical Procedure

8. The general arrangement of variables in the numerical grid system is identical to that used previously by Paul and Lick[1]. Horizontal velocities are defined at integral nodal points, temperature is defined at half-integral nodal points in the horizontal and integral nodal points in the vertical, and the surface pressure is defined at half-integral nodal points in the horizontal. Figures 2 and 3 are the horizontal grid and typical vertical grid sections for the nearshore model. The relative positions of the various variables within the numerical grid are depicted in these figures. The location of the jetport is indicated by shaded cells in Figure 2.

9. The finite difference approximations to the equations are derived by integrating the equations over nodal cells (Figure 4) using either the mid-point or trapezoidal integration rule to evaluate these integrals. In the derivation of the finite difference equations, a simple average of neighboring values is used for variables which are not defined at required points. The Euler explicit time scheme is used exclusively in the present model. Details of the finite difference approximation to the hydrodynamic equations are given in References 1 and 9.

10. Solution of the difference equations is obtained by the following scheme:

- a. Values from the previous time step are assumed to be available.
- b. Temperature is calculated by an explicit time scheme.
- c. Density is calculated from the equation of state.
- d. Surface pressure is calculated with the right-hand-side of the equation evaluated from the new temperatures and density values and other previous time step values.
- e. Horizontal velocities are calculated by an explicit time scheme.
- f. Vertical velocity is calculated by vertically integrating the continuity equation from the bottom.
- g. The present time step is now complete.

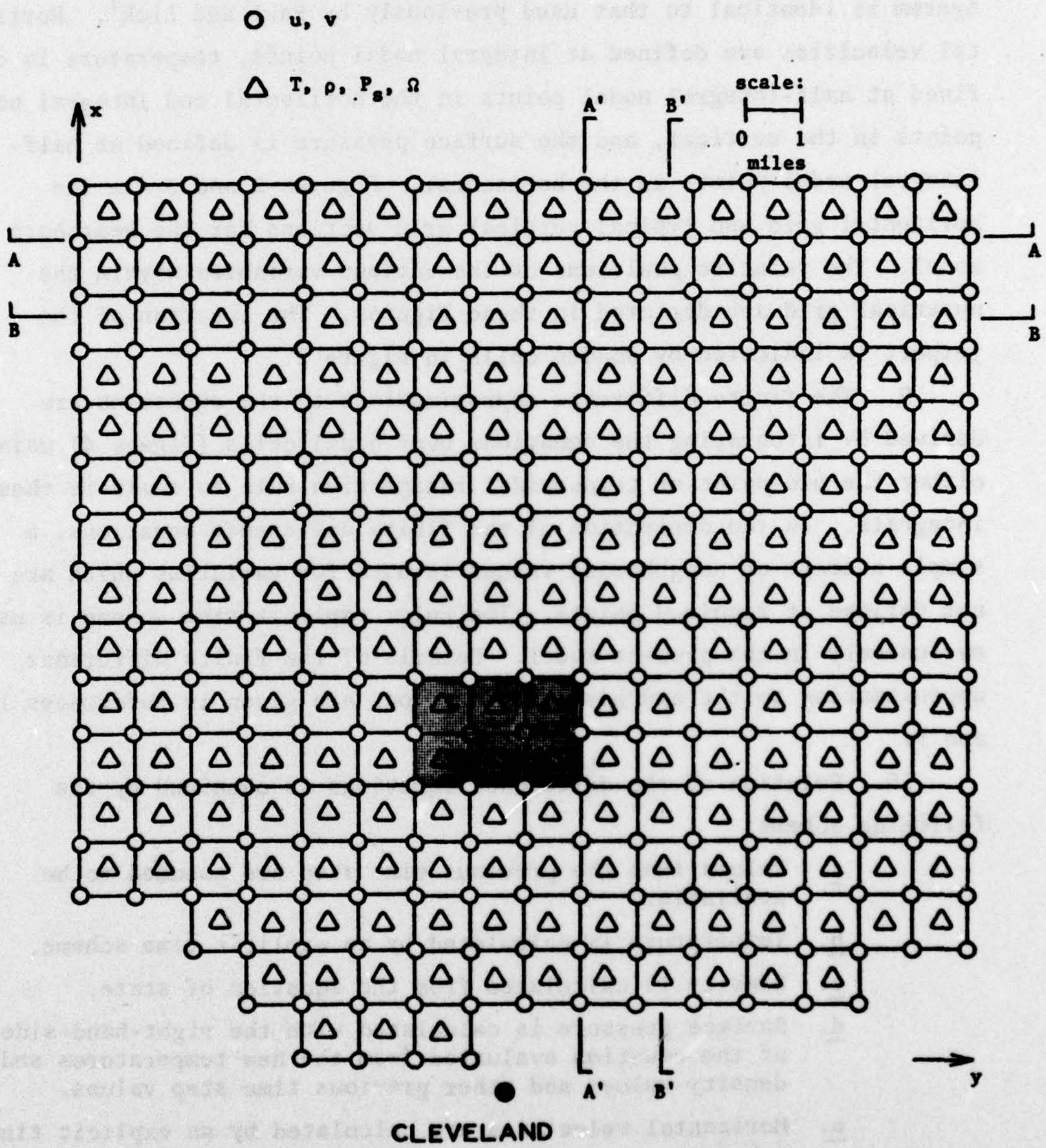
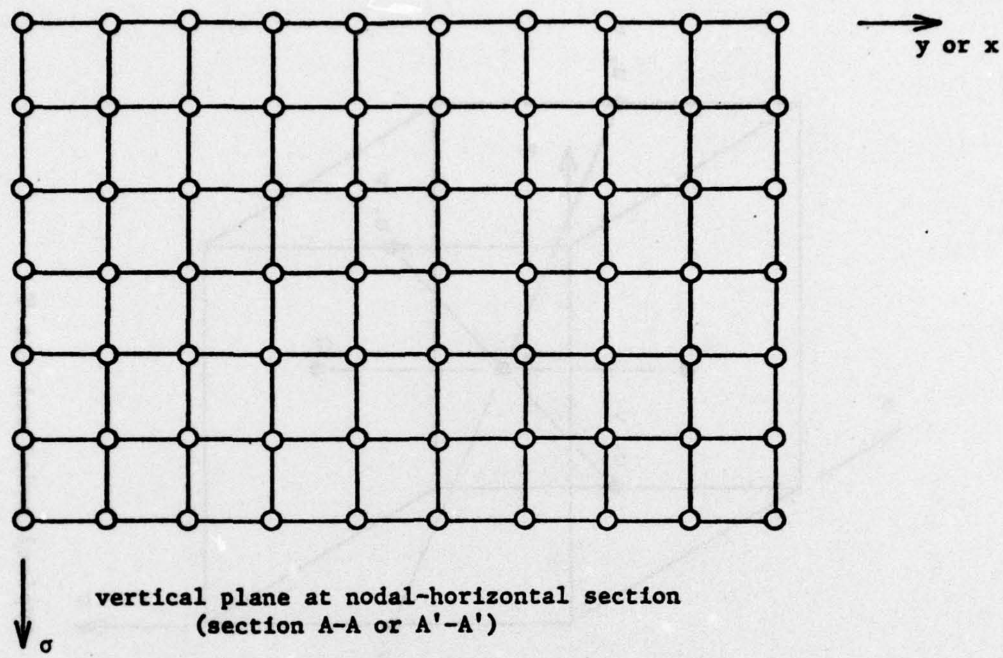
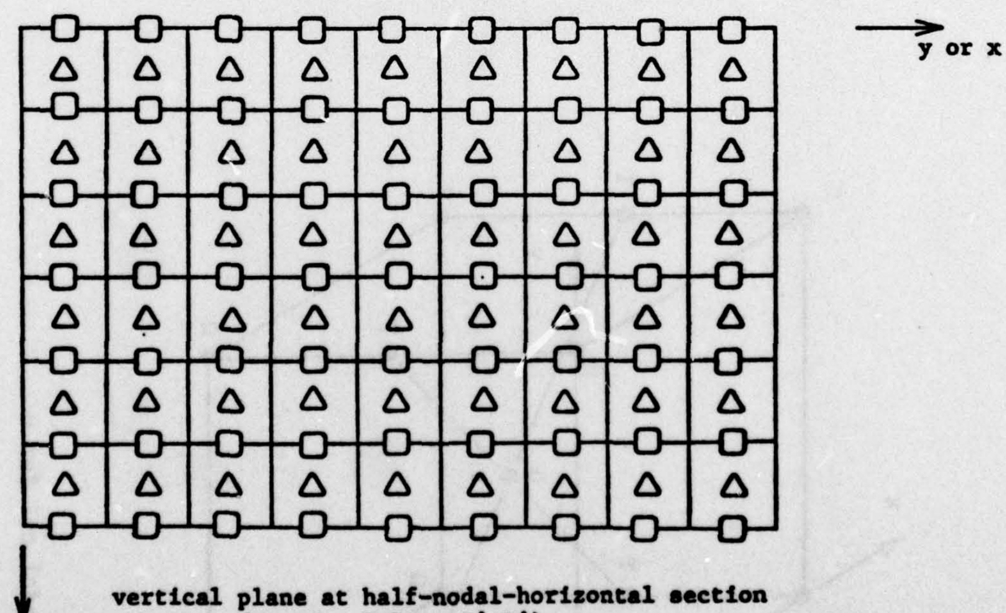


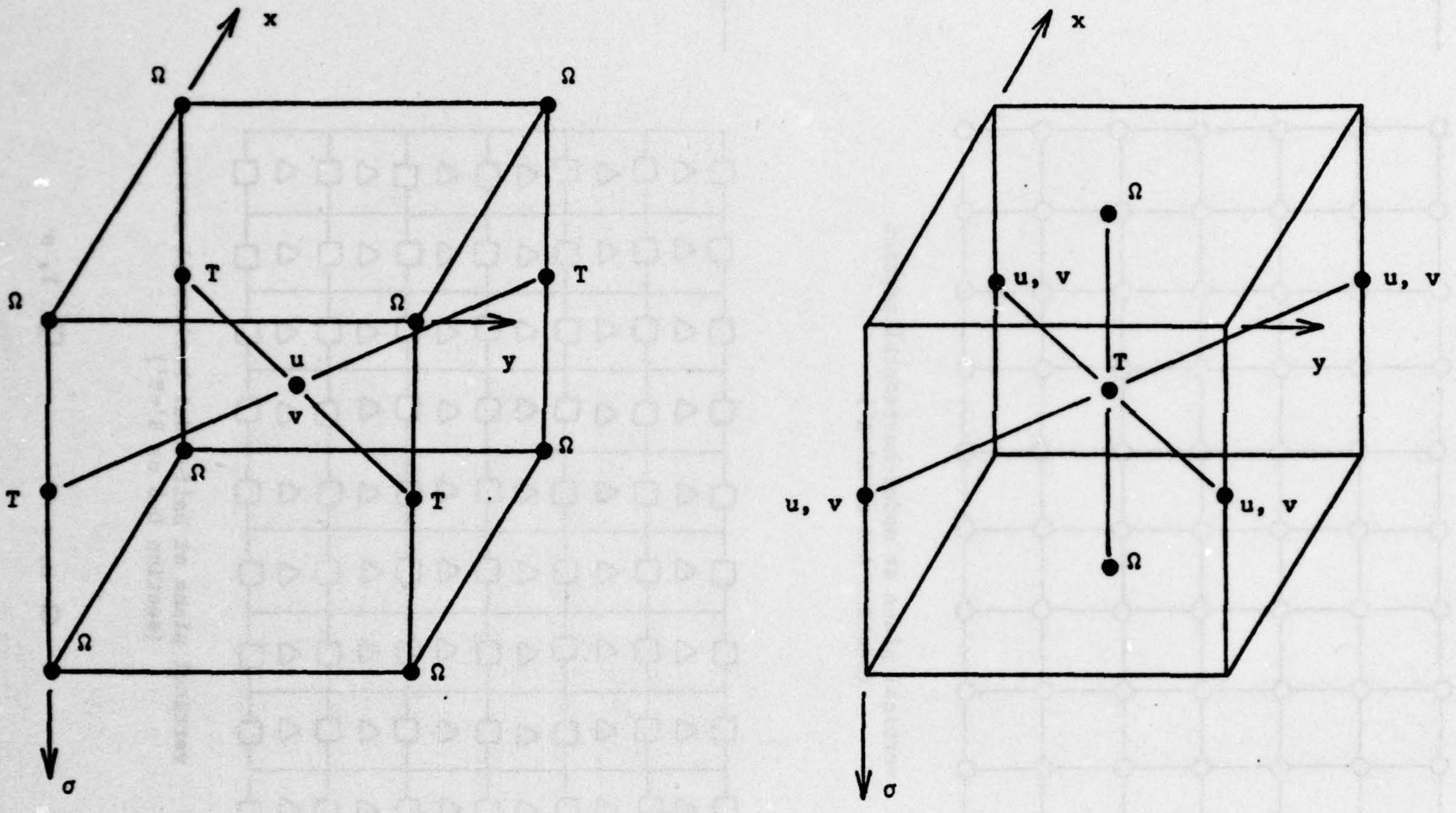
Figure 2. Location of variables within the horizontal grid for the nearshore model. Jetport island is indicated by shaded cells





△ Ω ○ u, v □ T, ρ

Figure 3. Location of variables in vertical sections for the nearshore model



typical nodal cel for u

typical nodal cel for T

Figure 4. Typical nodal cells for grid system

11. The temperatures are calculated by the explicit time scheme and are checked for static stability, i.e., if temperatures decrease monotonically downward (assuming that density increases with decreasing temperature). When static instabilities are encountered, an infinite mixing procedure[9] is used with temperatures over any unstable region being averaged. Using temperature values at new time steps, density is calculated from the equation of state of fresh water which is assumed to vary linearly with temperature.

12. At each time step, the Poisson equation for the surface pressure is solved by the point successive-over-relaxation (SOR) method. In the Poisson equation, the forcing term involves a time derivative of the vertical velocity at the surface. The vertical velocity at the surface is zero by the rigid-lid condition. However, non-zero values for the vertical velocity are obtained numerically by vertical integration of the continuity equation and indicate that the continuity equation can not be satisfied exactly by the finite difference solution. This error can grow in time; thus, the Hirt-Harlow corrective procedure[10] is used to correct for this error.

Nearshore Application

13. A particular finite difference grid depends on the actual geometry to be described. The shoreline used in this model is determined by the 20-ft contour. Zero depth is not chosen as the shoreline because the vertical coordinate transformation is singular for zero depths. This use of non-zero depth shorelines does not appreciably affect the boundary and is not a restriction on the model. The nearshore region, modeled in this study, is a 16-mile by 16-mile area in Lake Erie near Cleveland, Ohio, and is similar to the area used in previous WES studies.[3,8] A constant horizontal spacing of one mile is used with the proposed jetport represented by a two-mile by three-mile island five miles off Cleveland in approximately 50 ft of water (Figure 2).

14. The vertical eddy coefficient is taken as dependent on the local vertical temperature gradient. This form is similar to that suggested by Sundaram, et al (1969, 1970)[11,12] and is identical to that used in a previous application of this model.[13] The expression for the vertical eddy coefficient A_V is:

$$A_V = \alpha + \beta \frac{\partial T}{\partial z}$$

where α and β are constants dependent on the local conditions of the physical system modeled. The constant α is chosen so that in the absence of vertical temperature gradients, the eddy coefficient is equal to that which would be used for a constant eddy coefficient.

15. The wind stress imposed on the water surface due to the wind action is calculated from the formulae developed by Wilson (1960). These formulae have been successfully used in numerical calculations[3,4,8] of wind-driven circulations in lakes and in a previous application[13] of this present model to a power plant outfall.

16. Boundary conditions for the open water boundaries of the model are as follows:

a. Along the outer x boundary in the lake (boundary 3 of Figure 5), velocities and temperature are specified. Pressure is obtained from the vertically integrated x momentum equation. These boundary values of velocity and temperature were inferred using good engineering judgment from an application[1] of the numerical model to either the Central Basin of Lake Erie or the entire lake and WES results[3] of the steady-state, wind-driven circulation study.

b. Along the two y boundaries in the lake (boundaries 2 and 4 of Figure 5), the variables are assumed to be smoothly varying, i.e., the first normal derivatives of the velocities and temperature are zero and the second normal derivative of the pressure is zero.

17. In the non-dimensional formulation of the governing equations,[1,4,5] various characteristic parameters are defined and are used in scaling the non-dimensional results of the numerical study. A list of the pertinent parameters and their values, used in this study, is presented in Table 1.

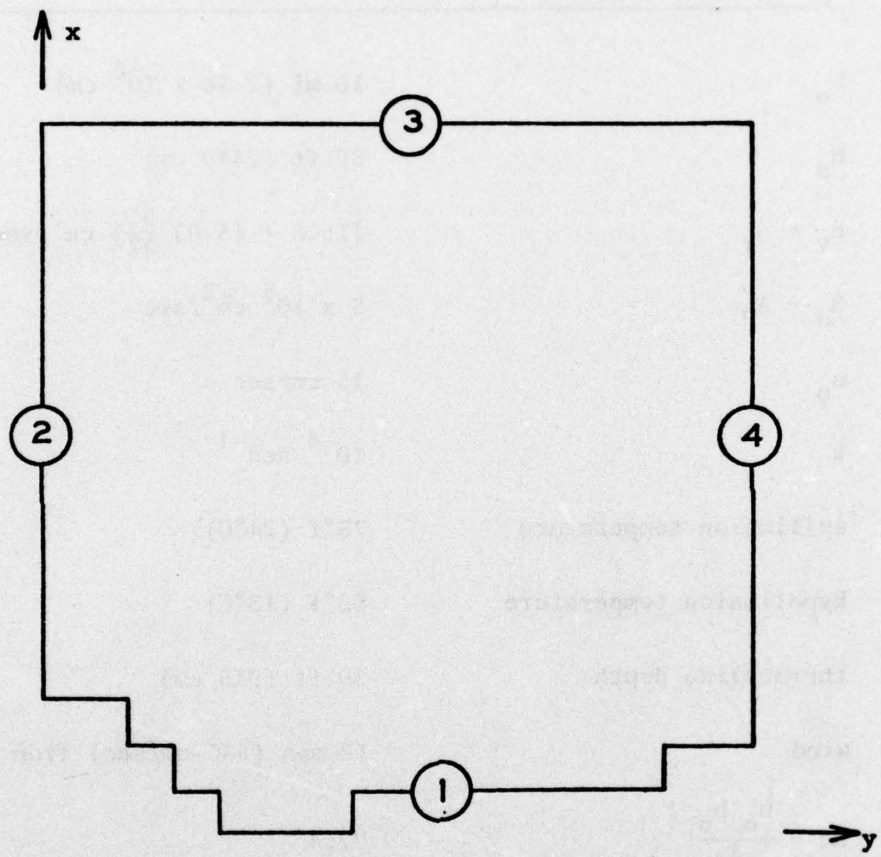


Figure 5. Boundaries for nearshore model

Table 1

Parameters Used in Application of Model

b_o	16 mi (2.58×10^6 cm)
h_o	80 ft (2440 cm)
$B_V = A_V$	$[16.8 + (5.0)\frac{\partial T}{\partial Z}]$ cm^2/sec
$B_H = A_H$	5×10^5 cm^2/sec
u_o	15 cm/sec
k	10^{-4} sec^{-1}
epilimnion temperature	75°f (24°C)
hypolimnion temperature	55°f (13°C)
thermocline depth	30 ft (915 cm)
wind	12 mph (536 cm/sec) from west
$Re = \frac{u_o\ b_o}{A_H}$	77.4
$Ro = \frac{k\ b_o^2}{A_H}$	1.33×10^3
$Fr = \frac{u_o}{\sqrt{g\ h_o}}$	9.6×10^{-3}

18. The numerical model,[1,4] which was developed at Case Western-Reserve University to compute three-dimensional, time-dependent, wind-driven currents for a thermally convective fluid in a nearshore region of Lake Erie, consisted of a Fortran code to compute the velocity components (u, v, and w), temperature, and density at any selected depth in the water column and pressure at the surface. The Waterways Experiment Station converted this code to operate on a CDC 7600 Computer and enhanced the output procedures to include various graphics routines.

PART III: RESULTS AND CONCLUSIONS

Results of Model Application

19. The numerical hydrodynamic model, described in Part II, has been used to investigate the effect of a proposed jetport island on the summer stratification pattern in the nearshore area offshore of Cleveland, Ohio. Due to monetary and time constraints in the feasibility study, only two steady-state wind fields were considered in studying the summer (stratified) lake conditions. The modal wind speed[2] (12 mph) and most frequently occuring direction[2] (SSE-SW) for the months of June, July, and August were considered as the typical steady-state summer wind field. This wind direction has an annual frequency of occurrence of 42 percent and a trimonth (June-August) frequency of occurence of 43 percent. A previous WES study[1] contracted to Case-Western Reserve University used the above wind field in studying the effects of a proposed jetport island on the summer circulation near Cleveland, Ohio. Results of this study are presented in detail in Reference 1. For this south wind direction, which produced minimum effects in the steady-state, wind-driven circulation for well-mixed (fall-winter) lake conditions[3], the effects of the proposed jetport island on the velocity regime were localized within 2 to 3 miles of the island. For the temperature regime, the effects of the proposed jetport island extend several miles from the island; however, these effects did not extend to the shoreline near Cleveland due to the particular direction (south) of the wind field. In addition to the above application (12 mph south wind), WES chose another steady-state wind field in studying the summer lake conditions. A 12 mph west wind was chosen for the second wind field since this direction produced maximum effects in the WES study[3] of steady-state, wind-driven circulation for well-mixed (fall-winter) lake conditions. Choosing a 12-mph modal wind speed and two wind directions (S&W) which produced the minimum and maximum jetport island effects in a previous WES study[3] of well-mixed lake conditions, the extreme effects of a jetport island on wind-driven circulation for stratified lake

conditions should be estimated sufficiently for this engineering feasibility study.

20. Results for the nearshore application of the hydrodynamic model without the jetport island for a 12 mph west wind are shown in Plates 13 to 24, and results with the jetport island are shown in Plates 25 to 36. In addition, vector plots of differences in horizontal velocity regimes with and without a jetport, contours of differences in velocity magnitude with and without a jetport, and contours of differences in temperature regimes with and without a jetport are presented in Plates 37 to 42, Plates 43 to 48, and Plates 49 to 54, respectively. The difference in horizontal velocity and temperature are computed by subtracting at each grid point in the nearshore region the velocity or temperature with a jetport from the velocity or temperature without a jetport. For contours of differences in velocity magnitude, the absolute values of the magnitude differences are contoured. For contours of temperature differences, a positive value indicates a higher temperature without the jetport and a negative value indicates a lower temperature without the presence of a jetport. Results are presented after 7.4 hrs of real time simulation. The initial conditions of horizontal velocity and temperature fields for the 12 mph west wind are indicated in Plates 1 to 6 and 7 to 12, respectively.

21. A comparison of horizontal velocity plots (Plates 13-20, 25-30, 37-42) indicate the proposed jetport's major effects on the horizontal velocity regime for a steady-state 12 mph west wind are localized within an area 3 to 4 miles from the jetport island. The areal extent and magnitude of change in the horizontal velocity regime that are associated with the proposed jetport are vividly depicted in Plates 37 to 48. In Plates 43 to 48, jetport perturbation of 0.25 ft/sec in the horizontal velocity regime extend to shore in the immediate vicinity of Cleveland, Ohio. These 0.25 ft/sec perturbations, which extend to shore, occur throughout the water column. The 0.25 ft/sec perturbations in horizontal velocity extend as much as 8 miles lakeward of the jetport. Velocity changes of 0.5 ft/sec extend a maximum of 4 miles from the jetport island and come within one mile of the shoreline near Cleveland,

Ohio. Velocity changes of 1 ft/sec extend a maximum of two miles from the jetport island with the maximum change of 1.5 ft/sec occurring at 20 ft depth in water column. The major influence of the proposed jetport island on the temperature structure in the lake extends 5 to 6 miles from the jetport island. The magnitude and areal extent of the jetport's effect on the horizontal isotherms are depicted in Plates 49 to 54. In addition, these contours of temperature differences vividly depict areas of upwelling of cool water and downwelling of warm water around the jetport. Temperature changes of 0.5^{o} (F) occur along the shoreline in the immediate vicinity of Cleveland, Ohio. Temperature changes of 1.0^{o} (F) extend within a half mile of the shoreline and 5-1/2 miles lakeward of the jetport island. Temperature changes of 5.0^{o} (F) or greater are confined within 2-1/2 miles from the island. The largest decrease (14^{o}F) in temperature occurs at the water surface in the strong upwelling region along the southern side of the jetport island. *Large increases (16^{o}F) in temperature* occur at 40-ft depth in the water column in the strong downwelling region along the northern side of the jetport island.

22. The large area of influence by the proposed jetport island in temperature regime and horizontal velocity can be associated with the upwelling and downwelling regions which change the stratification structure in the lake around the jetport. Being a variable-density model, changes in the temperature structure cause changes in the velocity patterns. Therefore, these strong upwelling and downwelling regions produce mixing between the hypolimnion and the epilimnion in this region of the lake and can result in the erosion of the thermocline in this area. The results of this model are dependent of the wind direction with shape, size, and location of upwelling and downwelling depending on wind speed and direction. In addition, the area of influence by the jetport would be expected for a constant wind field to change with time (increasing in areal extent into lake with time). Values (Table 1) for various parameters, in particular the vertical eddy diffusivity coefficient[14], have a large effect on the vertical temperature structure which, in turn, influences the velocity regime. Further experimentation with

the numerical model would be required to determine the influence of various parameters. Additional confidence in the model results could be obtained by comparing results of model without a jetport with prototype data. However, no prototype data are available at this time for such model verification. Thus, the results presented in this report should be considered preliminary and capable of defining for engineering feasibility purposes the qualitative effects of a proposed jetport island on the thermal structure and horizontal velocity in the lake for a steady-state 12 mph west wind.

Conclusions

23. General conclusions of WES numerical model study of the effects of a proposed jetport island on the wind-driven circulation in Lake Erie for thermally stratified lake conditions with a 12 mph west wind are presented below:

a. The jetport island's effects of an engineering and practical interest are confined within a 16 mile by 16 mile nearshore region with major effects in velocity and thermal regimes being localized near the jetport island.

b. Due to the presence of a jetport island, horizontal velocity changes of 0.25 ft/sec extend as much as 8 miles lakeward of the jetport and reach the shoreline in the immediate vicinity of Cleveland, Ohio. Velocity changes of 0.5 ft/sec extend lakeward a maximum of 4 miles from the jetport and reach within 1 mile of the shore near Cleveland. Velocity changes of 1 ft/sec or greater are confined within 2 miles of the jetport. The maximum change in horizontal velocity is estimated to be 1.5 ft/sec.

c. The jetport's effects on thermal structure extends lakeward 5 to 10 miles from the jetport with 0.5^{o} (F) changes in temperature reaching the shoreline near Cleveland, Ohio. Temperature changes of 1^{o} (F) extend within a half mile of the Cleveland shoreline and 5 to 6 miles lakeward of the jetport. Changes of 5^{o} (F) or greater are confined within 2-1/2 miles of the jetport. Maximum temperature changes of approximately 15^{o} (F) are estimated in the areas of strong upwelling and downwelling along the jetport island's perimeter.

d. The location, size, and shape of areas of upwelling and downwelling around the jetport island are dependent on wind speed and direction. These areas induce mixing between the epilimnion and hypolimnion layers, and can cause erosion of the thermocline in the immediate vicinity of the jetport island.

e. For the 12 mph west wind, the downwelling along the shore northeast of Cleveland is basically not affected.

24. Based on above results of this study, a 2 mile by 3 mile jetport island located in Lake Erie at least 4 miles offshore of Cleveland, Ohio will change the horizontal velocity regime and thermal structure in the immediate vicinity of Cleveland, Ohio. Although these effects appear to be small (0.25 ft/sec and $0.5^{\circ}F$), their impact on the circulation within the Cleveland Harbor need to be studied. Effects of an engineering interest occur within 3 to 5 miles of the proposed jetport island. These results are preliminary, have not been verified using prototype data, and should be used in the feasibility study to indicate the qualitative effects of the proposed jetport island on the wind-driven circulation in Lake Erie for thermally stratified lake conditions with a 12 mph west wind.

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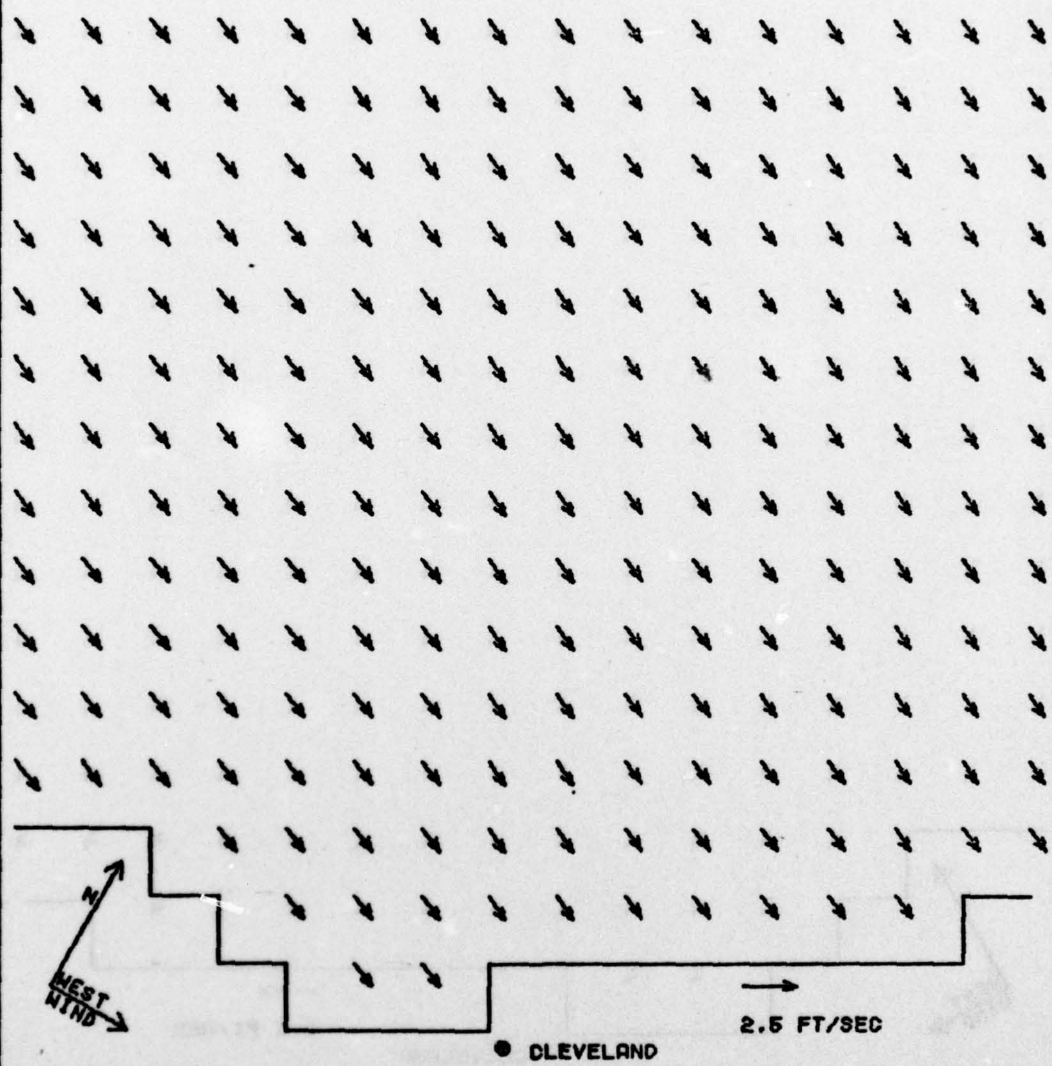
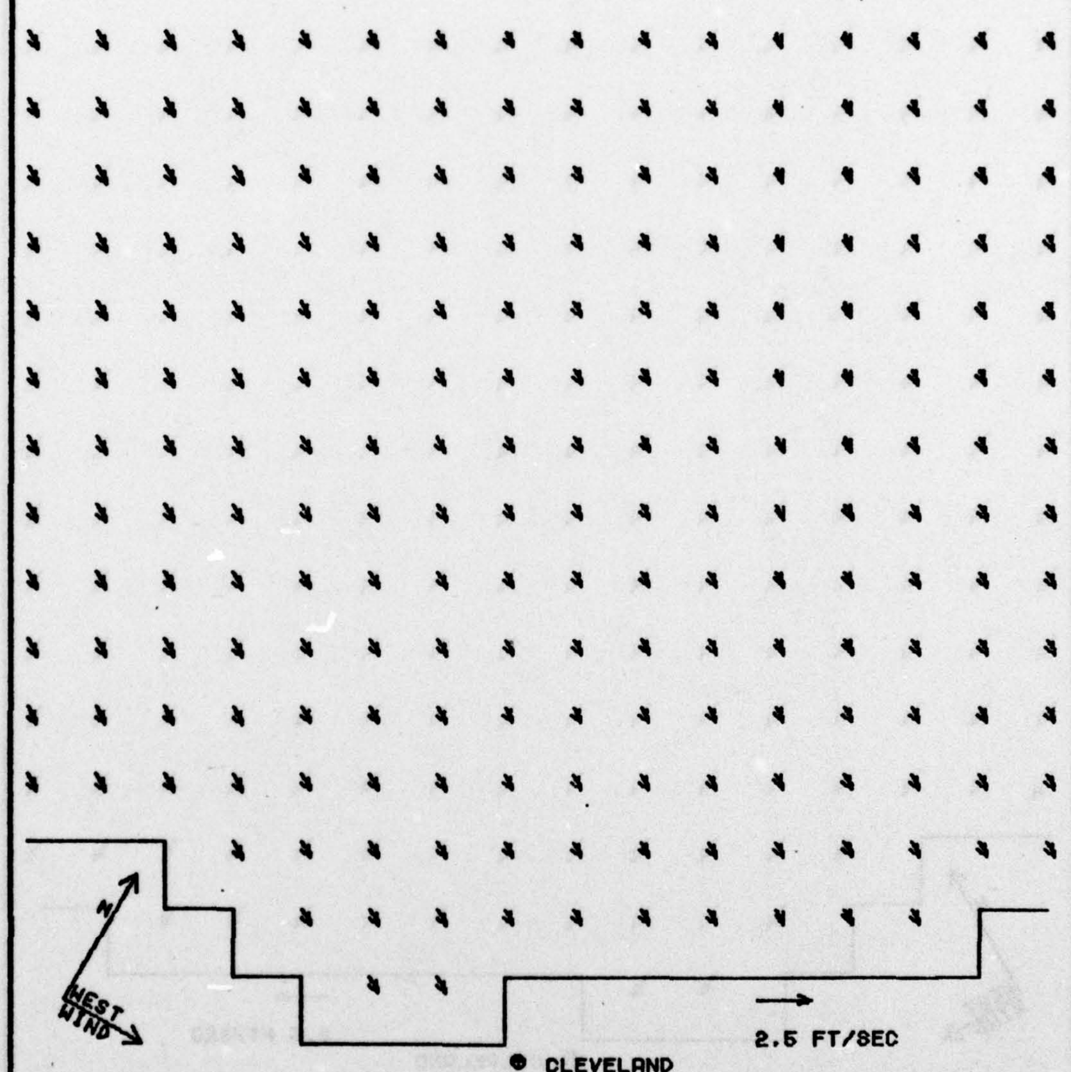


HORIZONTAL VELOCITY AT 0 FT DEPTH

12 MPH WEST WIND

INITIAL CONDITIONS WITHOUT JETPORT

PLATE 1

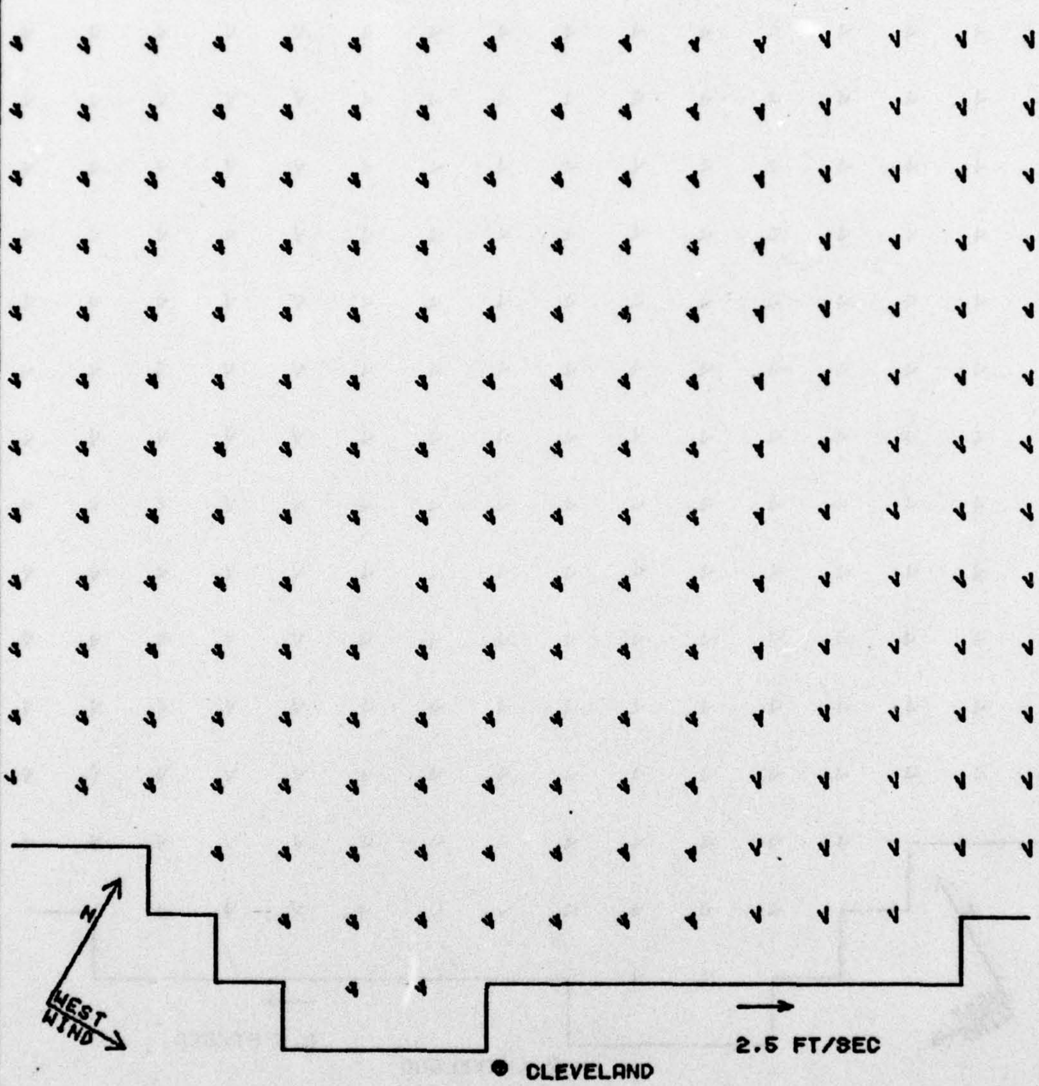


HORIZONTAL VELOCITY AT 10 FT DEPTH

12 MPH WEST WIND

INITIAL CONDITIONS WITHOUT JETPORT

PLATE 2



HORIZONTAL VELOCITY AT 15 FT DEPTH

12 MPH WEST WIND

INITIAL CONDITIONS WITHOUT JETPORT

PLATE 3

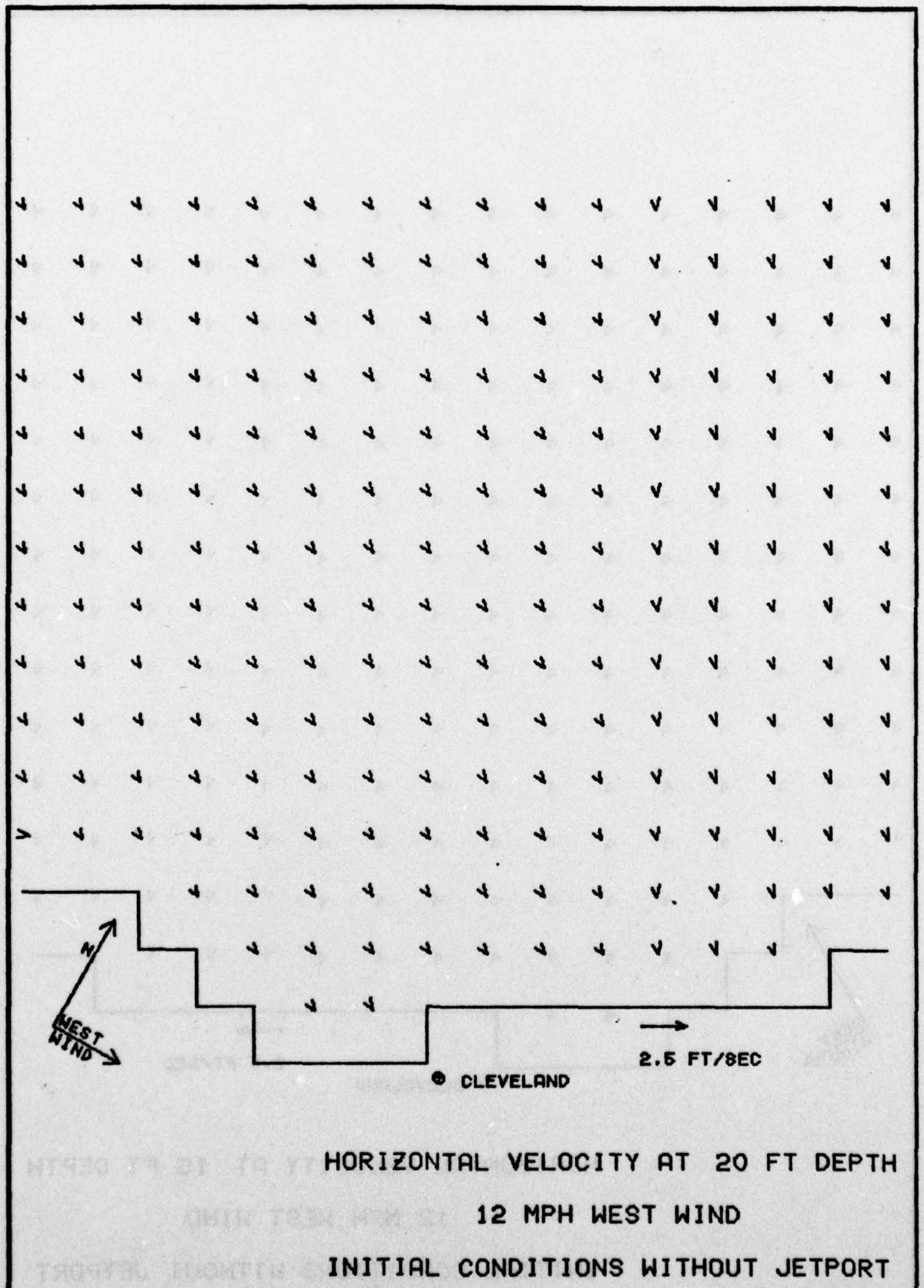
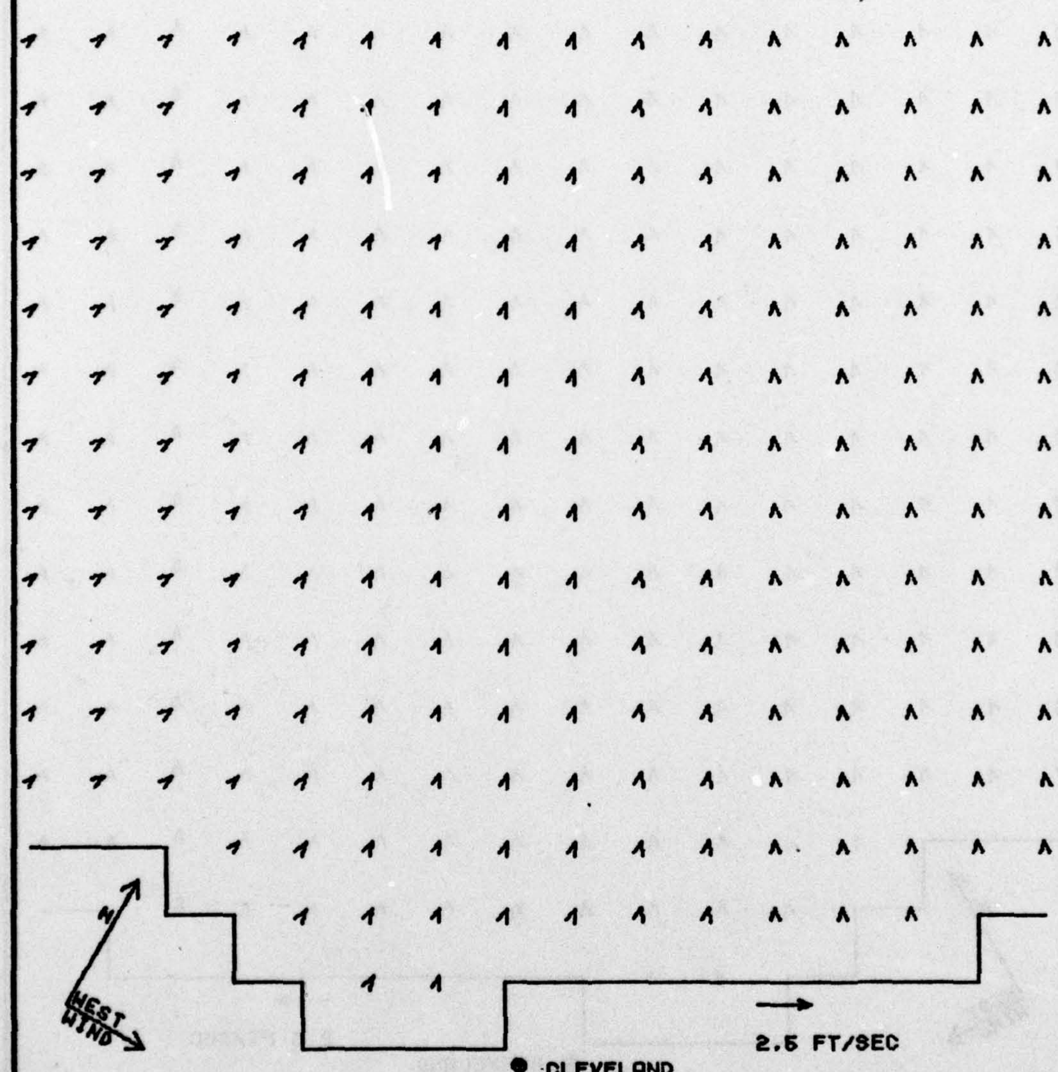

N
WEST WIND
2.5 FT/SEC
CLEVELAND
HORIZONTAL VELOCITY AT 20 FT DEPTH
12 MPH WEST WIND
INITIAL CONDITIONS WITHOUT JETPORT

PLATE 4

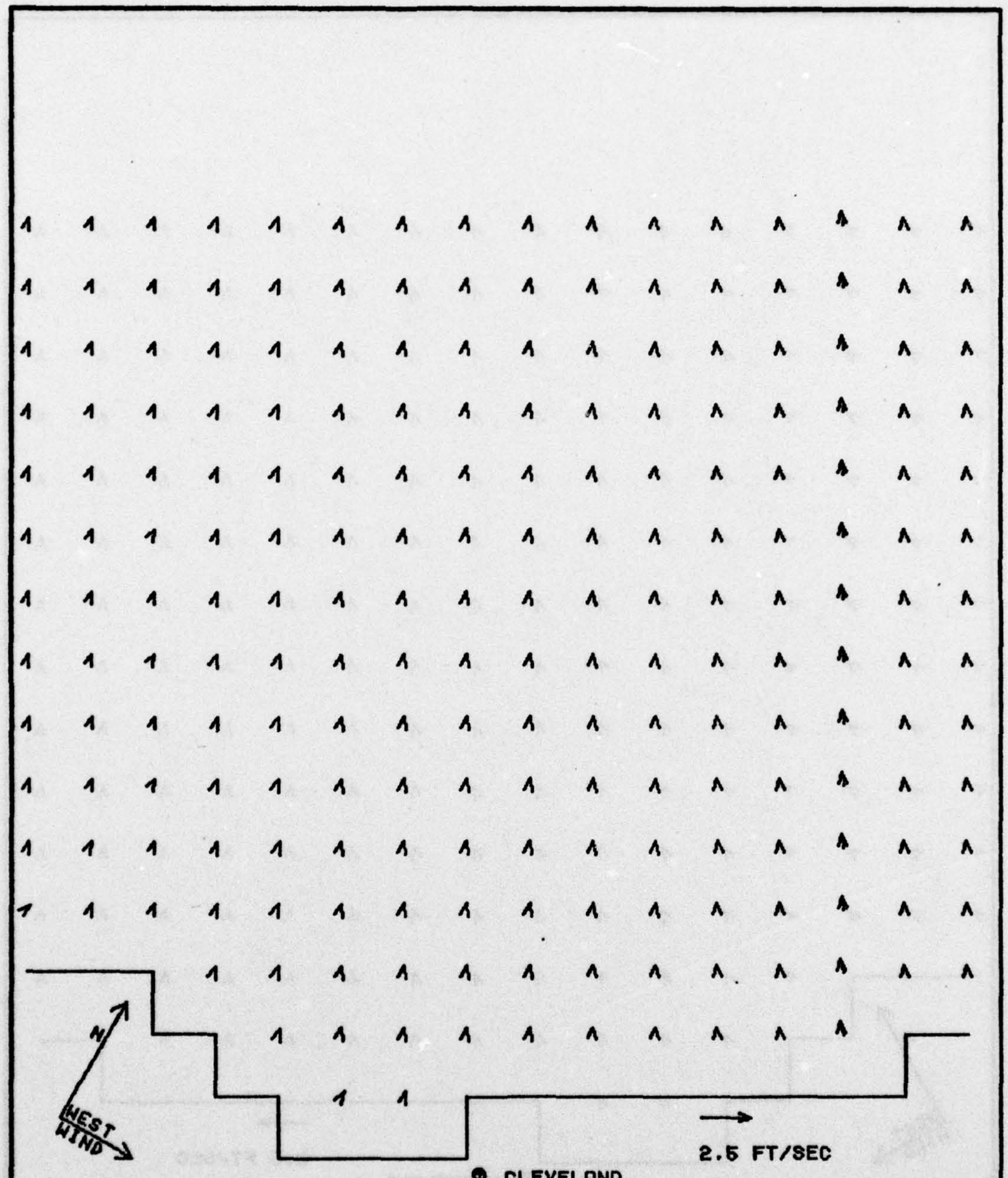


HORIZONTAL VELOCITY AT 30 FT DEPTH

12 MPH WEST WIND

INITIAL CONDITIONS WITHOUT JETPORT

PLATE 5

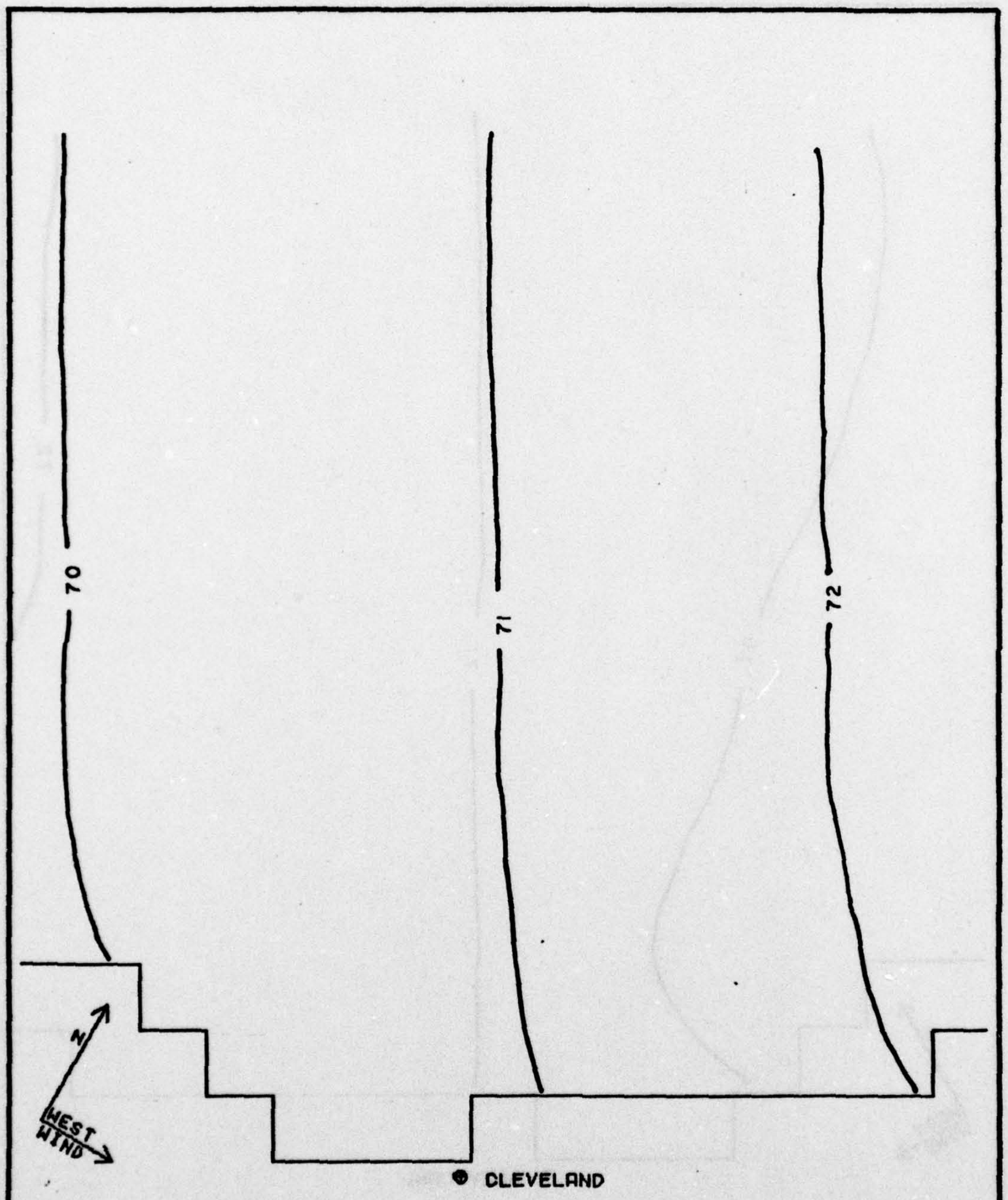


HORIZONTAL VELOCITY AT 40 FT DEPTH

12 MPH WEST WIND

INITIAL CONDITIONS WITHOUT JETPORT

PLATE 6

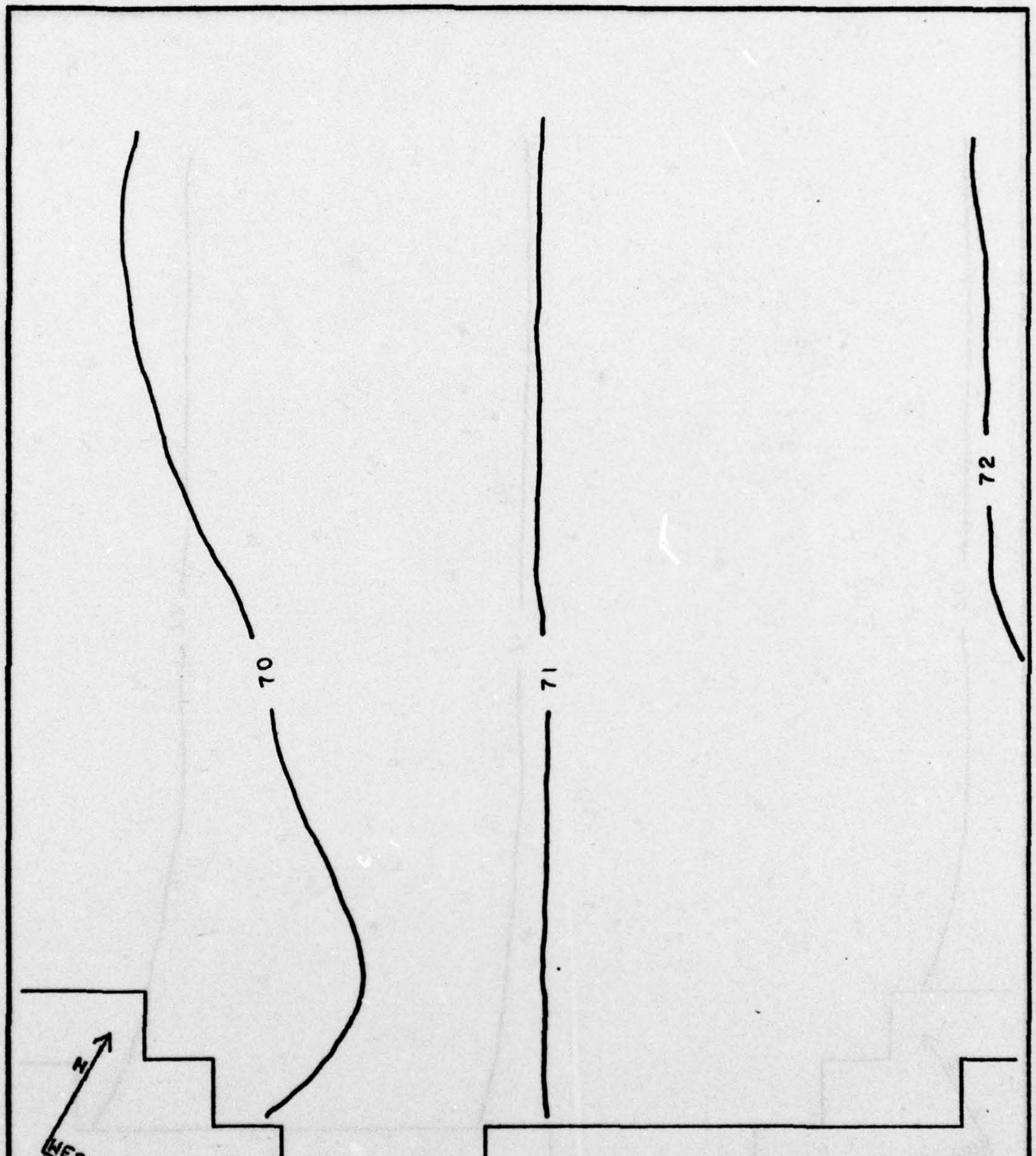


TEMPERATURE AT 0 FT DEPTH

12 MPH WEST WIND

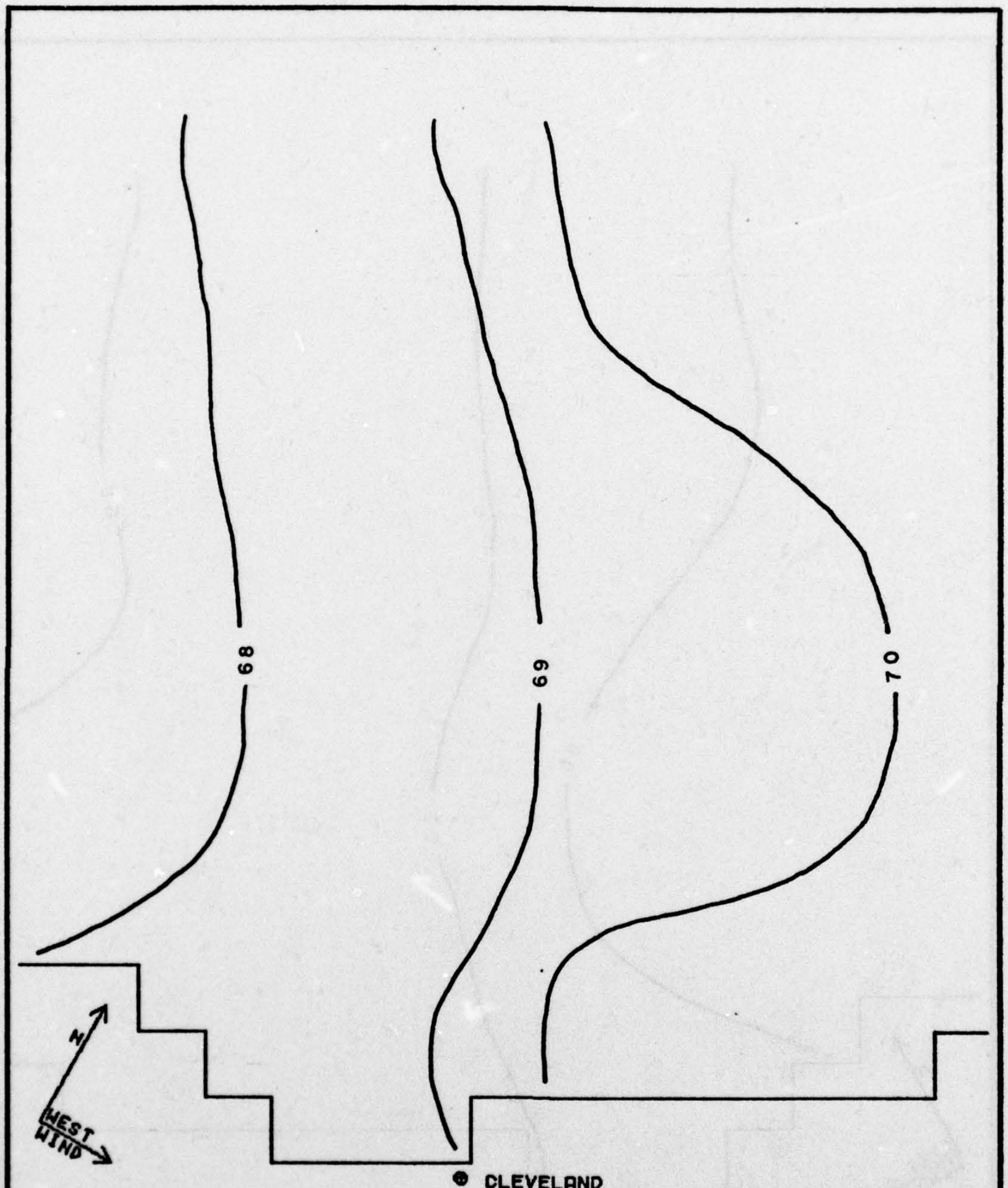
INITIAL CONDITIONS WITHOUT JETPORT

PLATE 7



70
71
72
N
WEST WIND
CLEVELAND
TEMPERATURE AT 10 FT DEPTH
12 MPH WEST WIND
INITIAL CONDITIONS WITHOUT JETPORT

PLATE 8



TEMPERATURE AT 15 FT DEPTH

12 MPH WEST WIND

INITIAL CONDITIONS WITHOUT JETPORT

PLATE 9

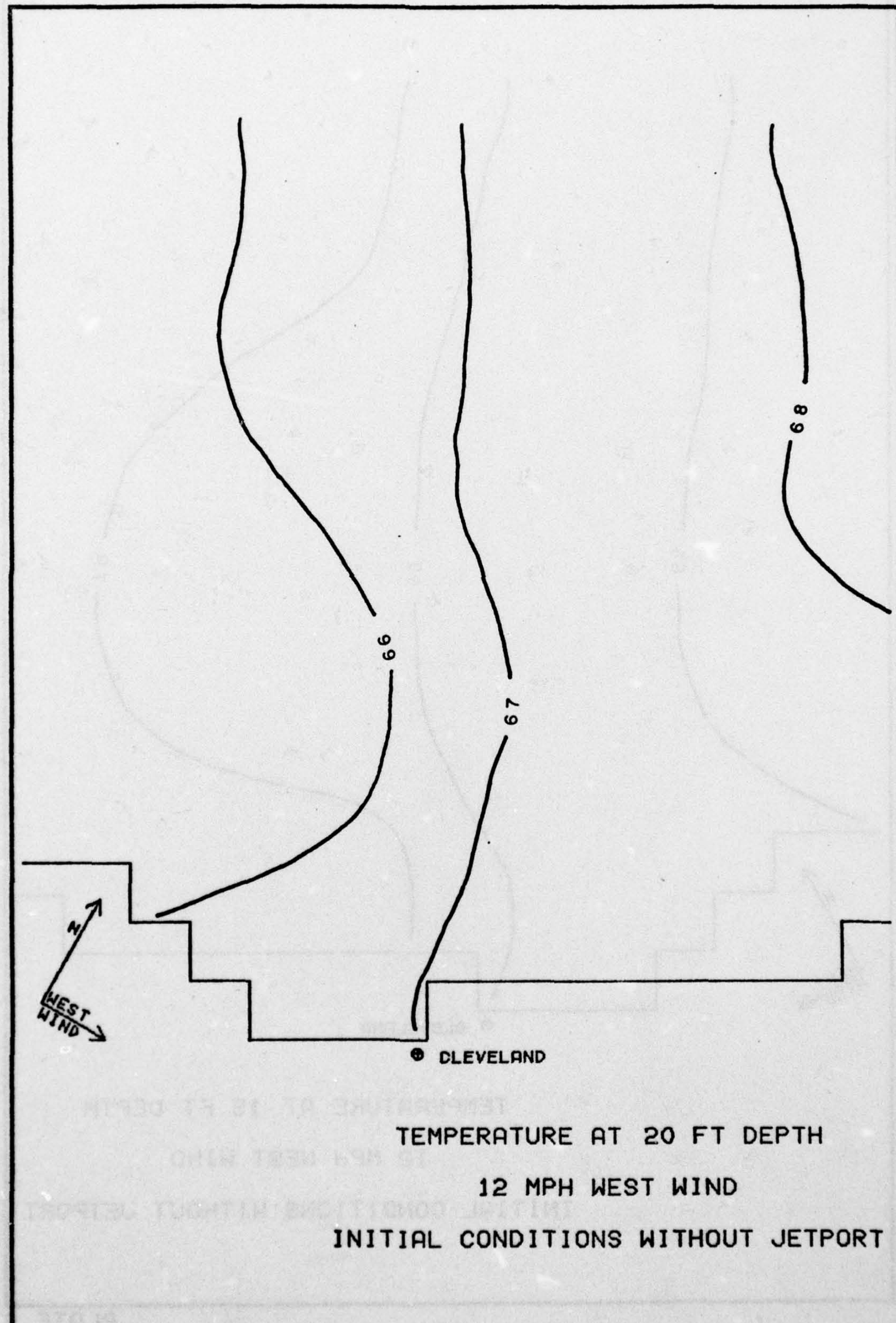
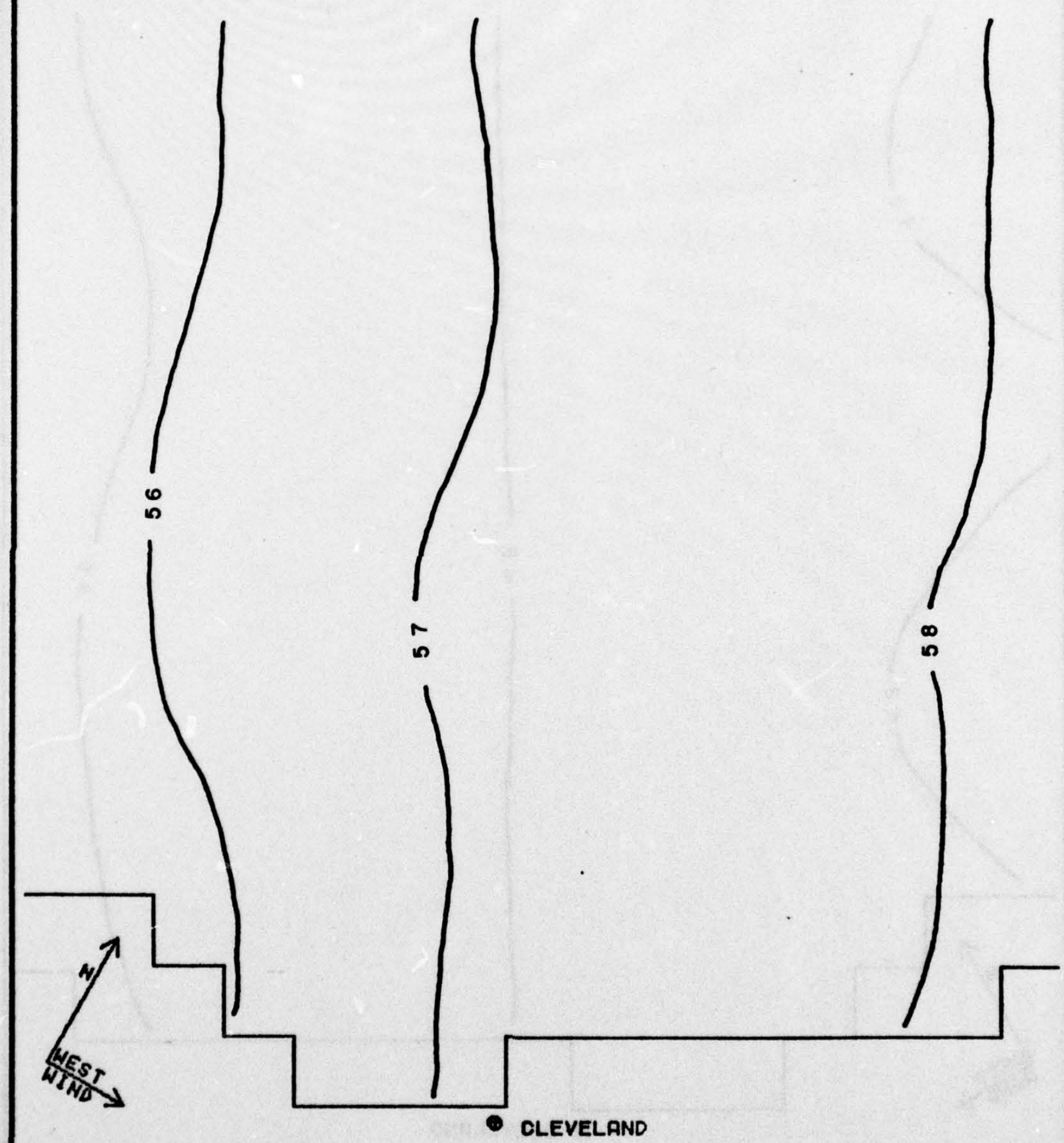

68
66
67
N
WEST WIND
CLEVELAND
TEMPERATURE AT 20 FT DEPTH
12 MPH WEST WIND
INITIAL CONDITIONS WITHOUT JETPORT

PLATE 10



TEMPERATURE AT 30 FT DEPTH

12 MPH WEST WIND

INITIAL CONDITIONS WITHOUT JETPORT

PLATE 11

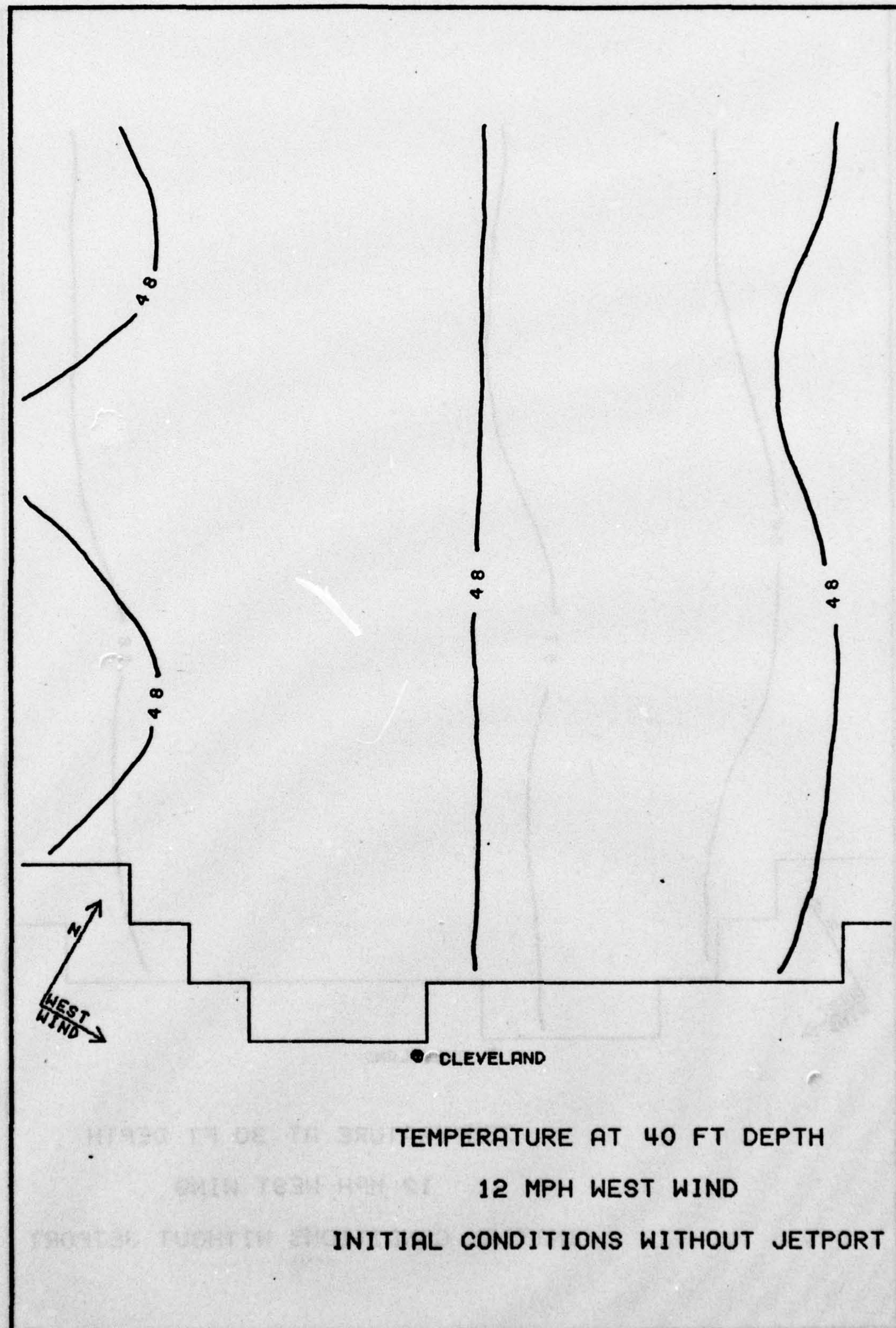
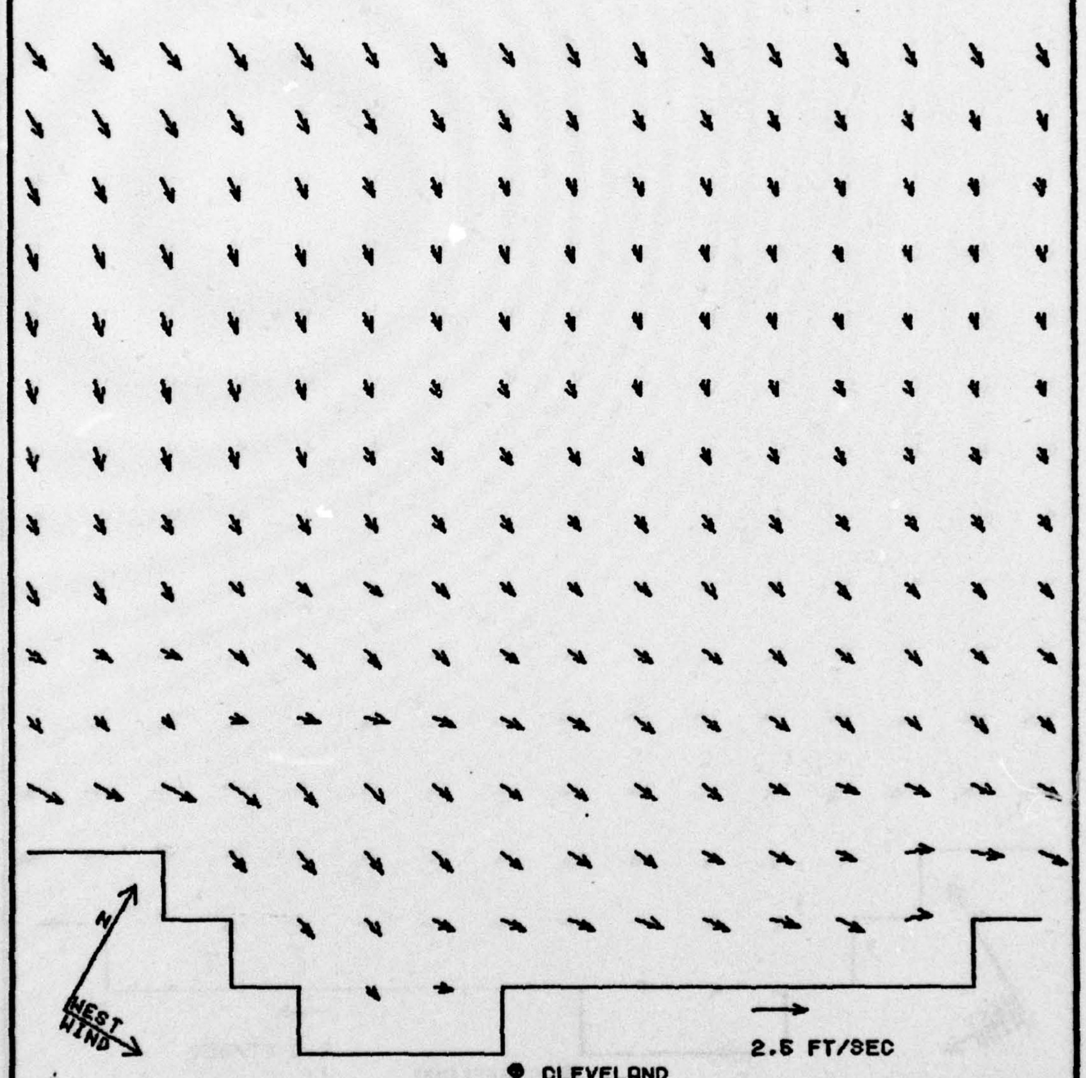

48
48
48
48
N
WEST WIND
CLEVELAND
TEMPERATURE AT 40 FT DEPTH
12 MPH WEST WIND
INITIAL CONDITIONS WITHOUT JETPORT

PLATE 12

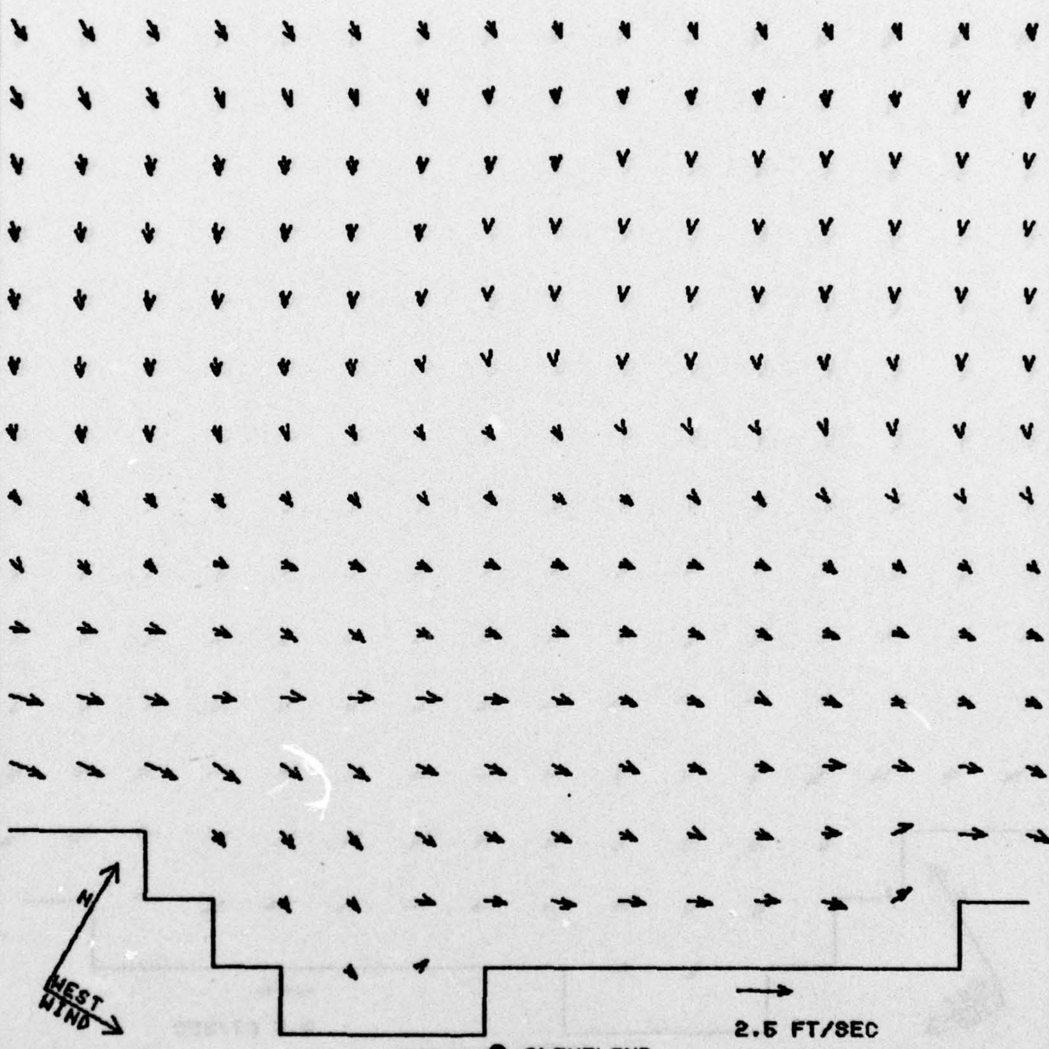


HORIZONTAL VELOCITY AT 0 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION WITHOUT JETPORT

PLATE 13

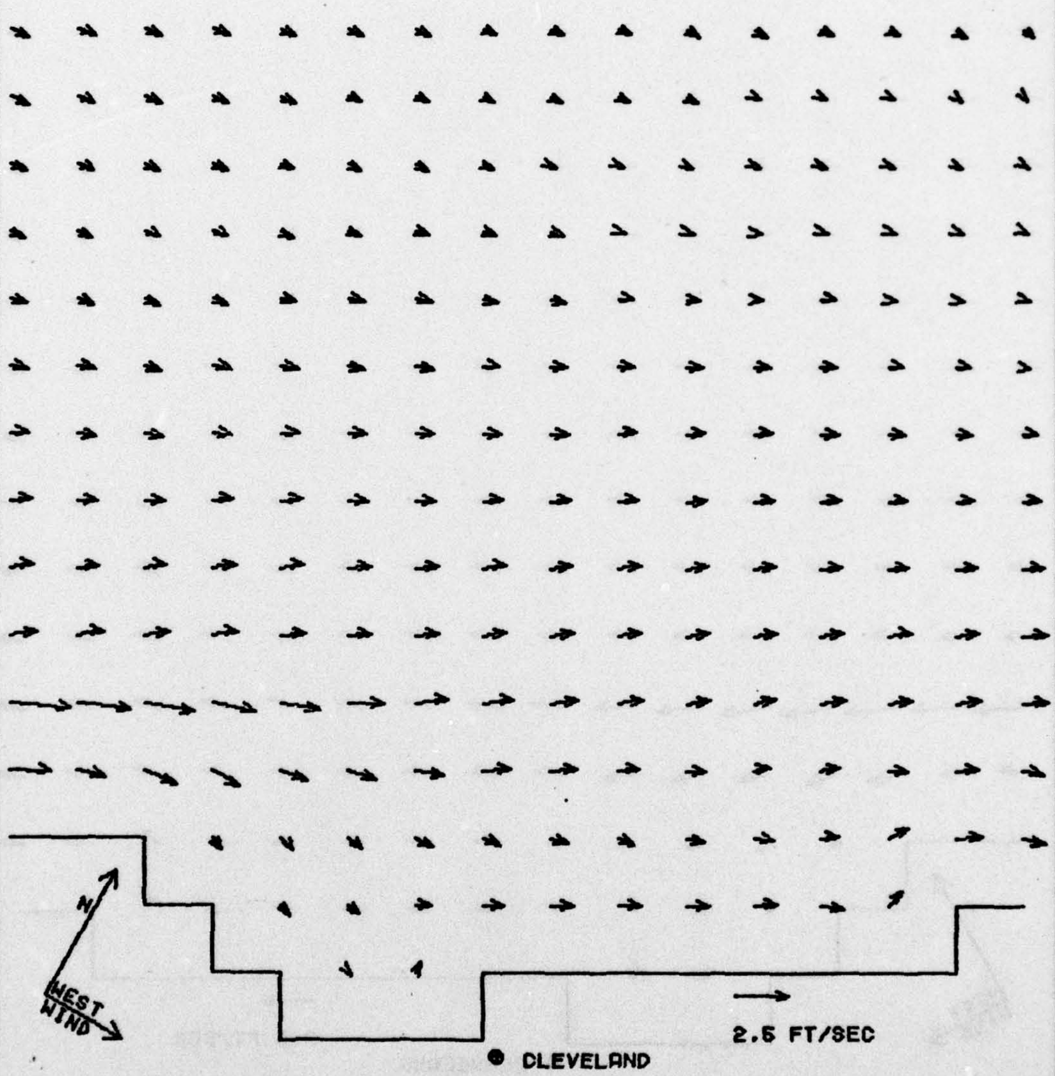


HORIZONTAL VELOCITY AT 10 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION WITHOUT JETPORT

PLATE 14



HORIZONTAL VELOCITY AT 15 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION WITHOUT JETPORT

PLATE 15

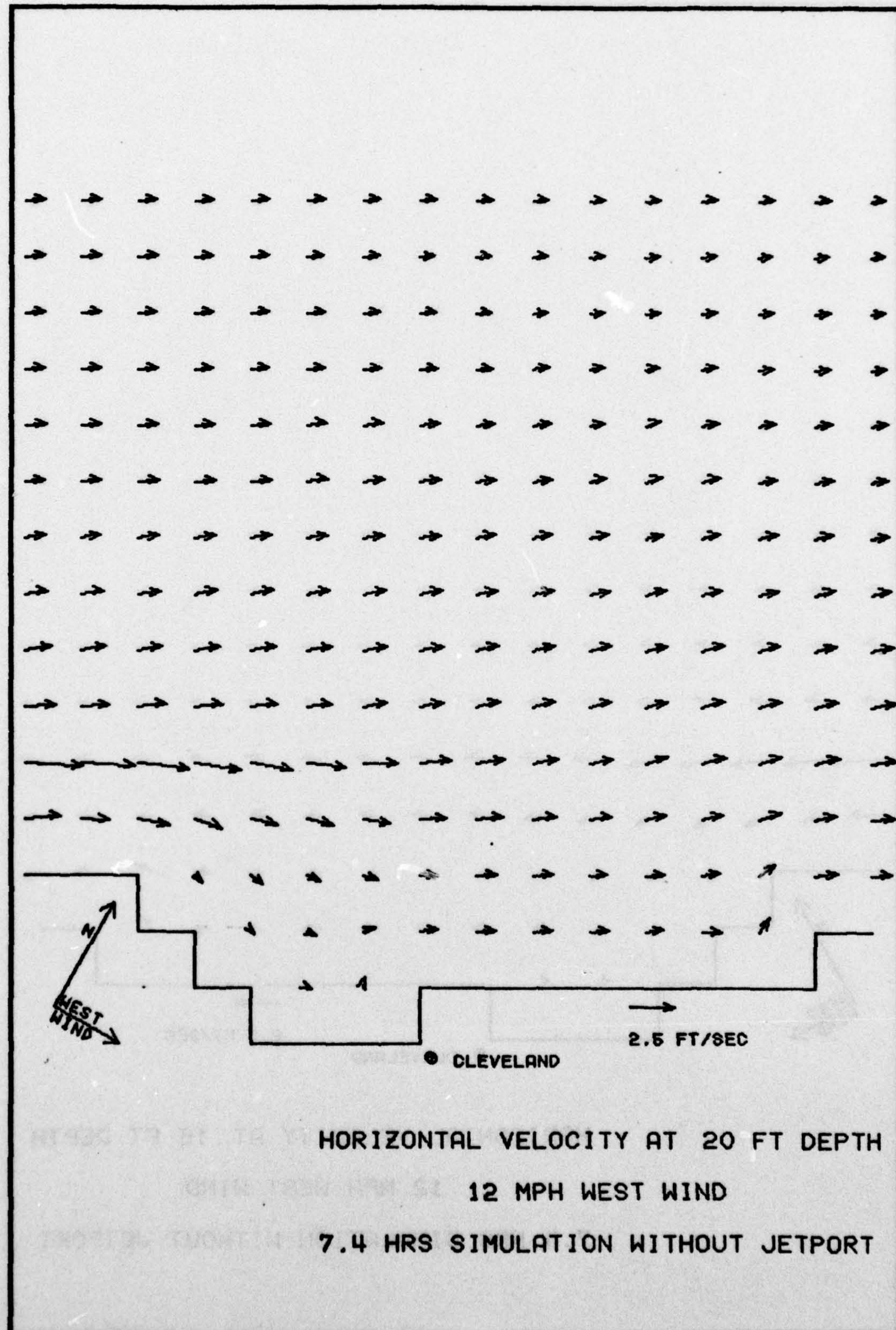
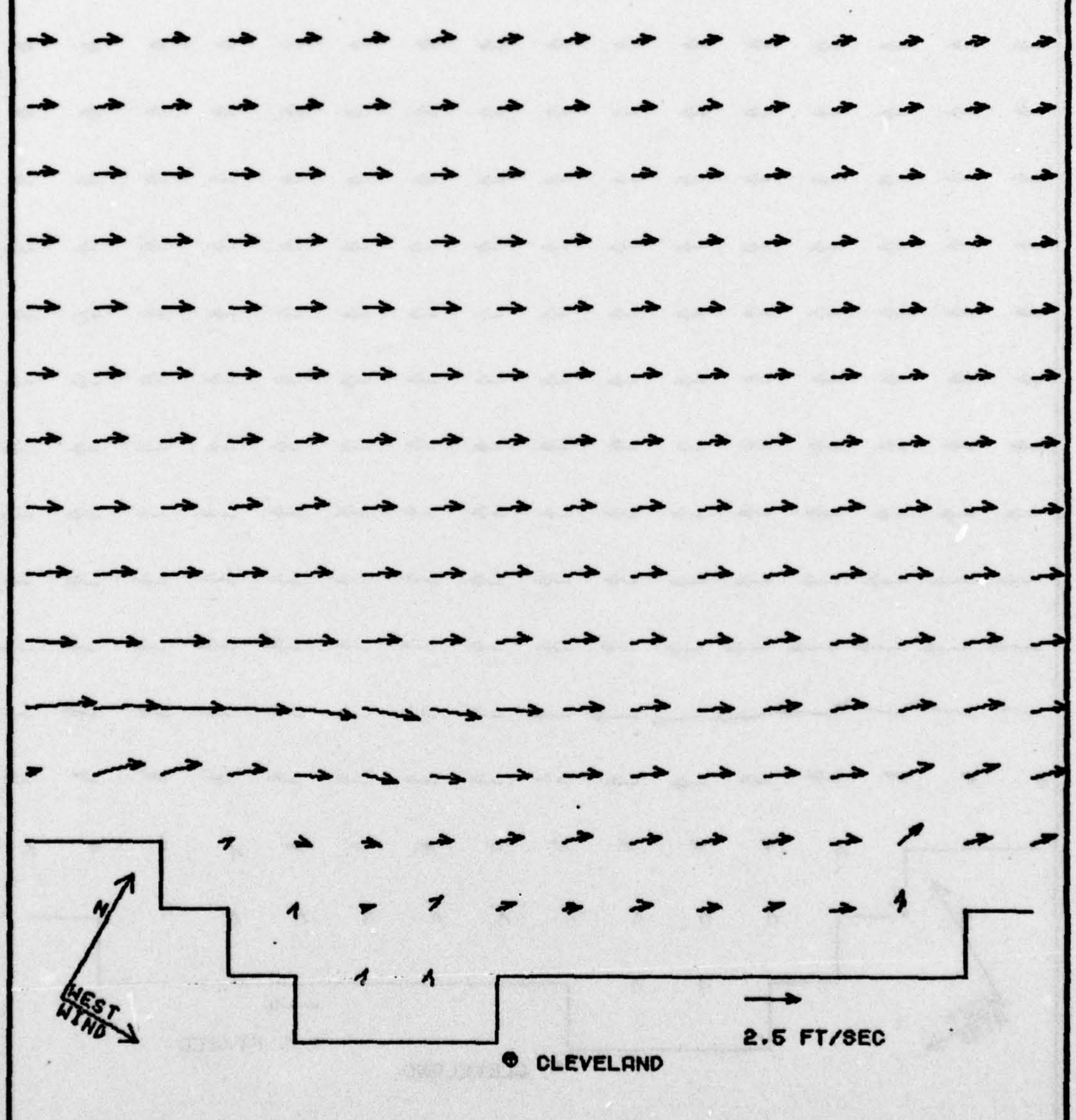

N
WEST WIND
2.5 FT/SEC
CLEVELAND
HORIZONTAL VELOCITY AT 20 FT DEPTH
12 MPH WEST WIND
7.4 HRS SIMULATION WITHOUT JETPORT

PLATE 16

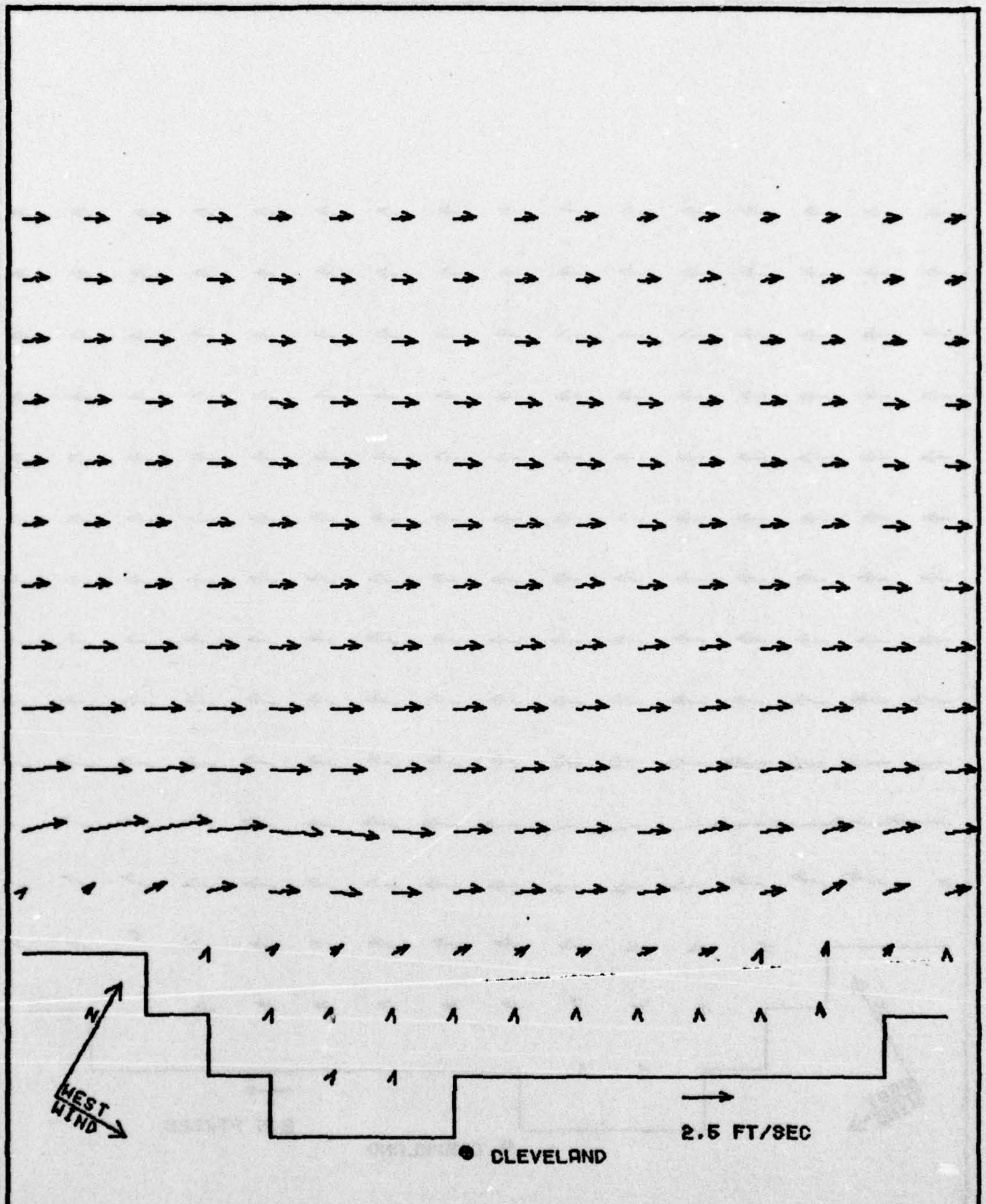


HORIZONTAL VELOCITY AT 30 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION WITHOUT JETPORT

PLATE 17

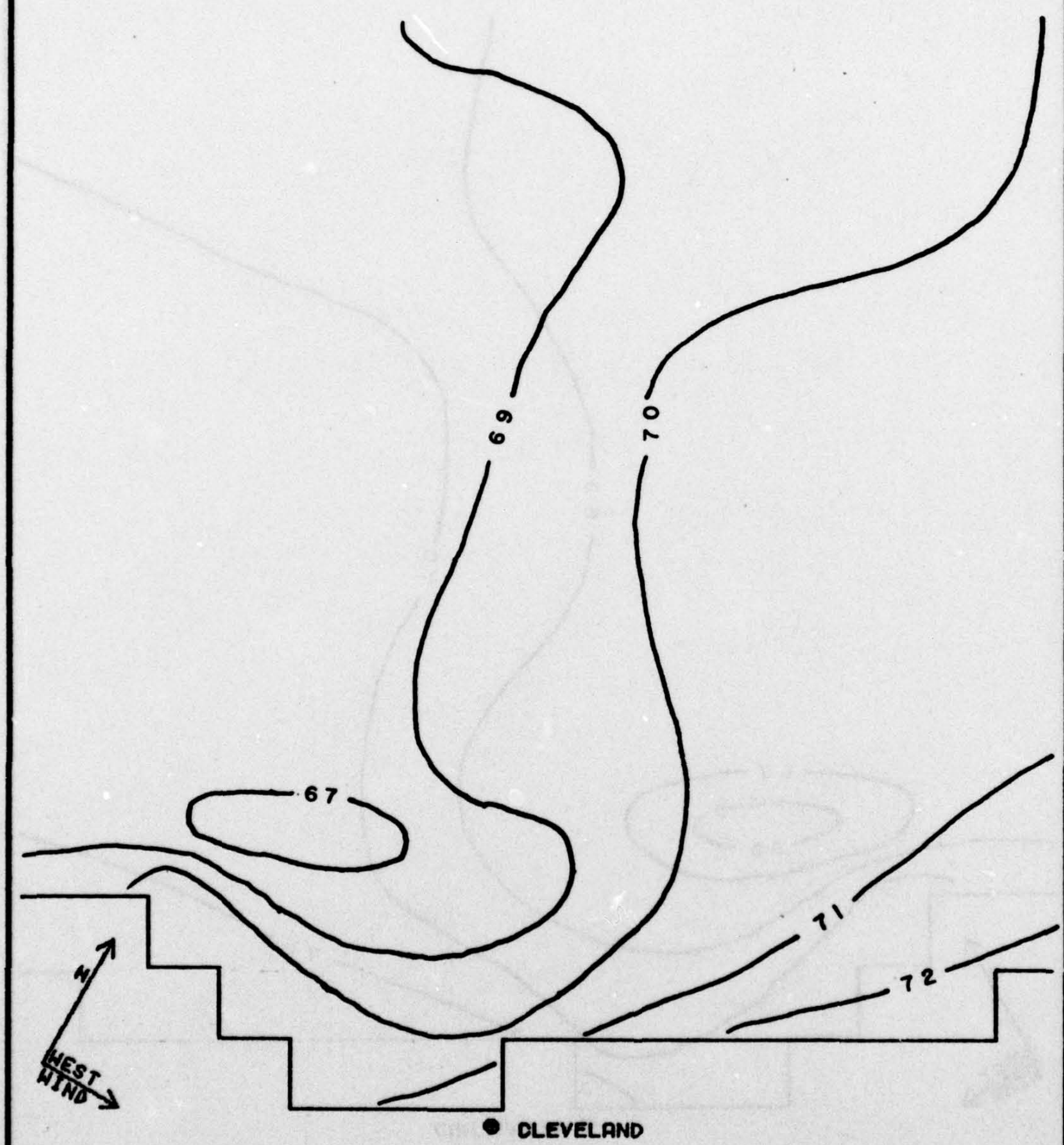


HORIZONTAL VELOCITY AT 40 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION WITHOUT JETPORT

PLATE 18

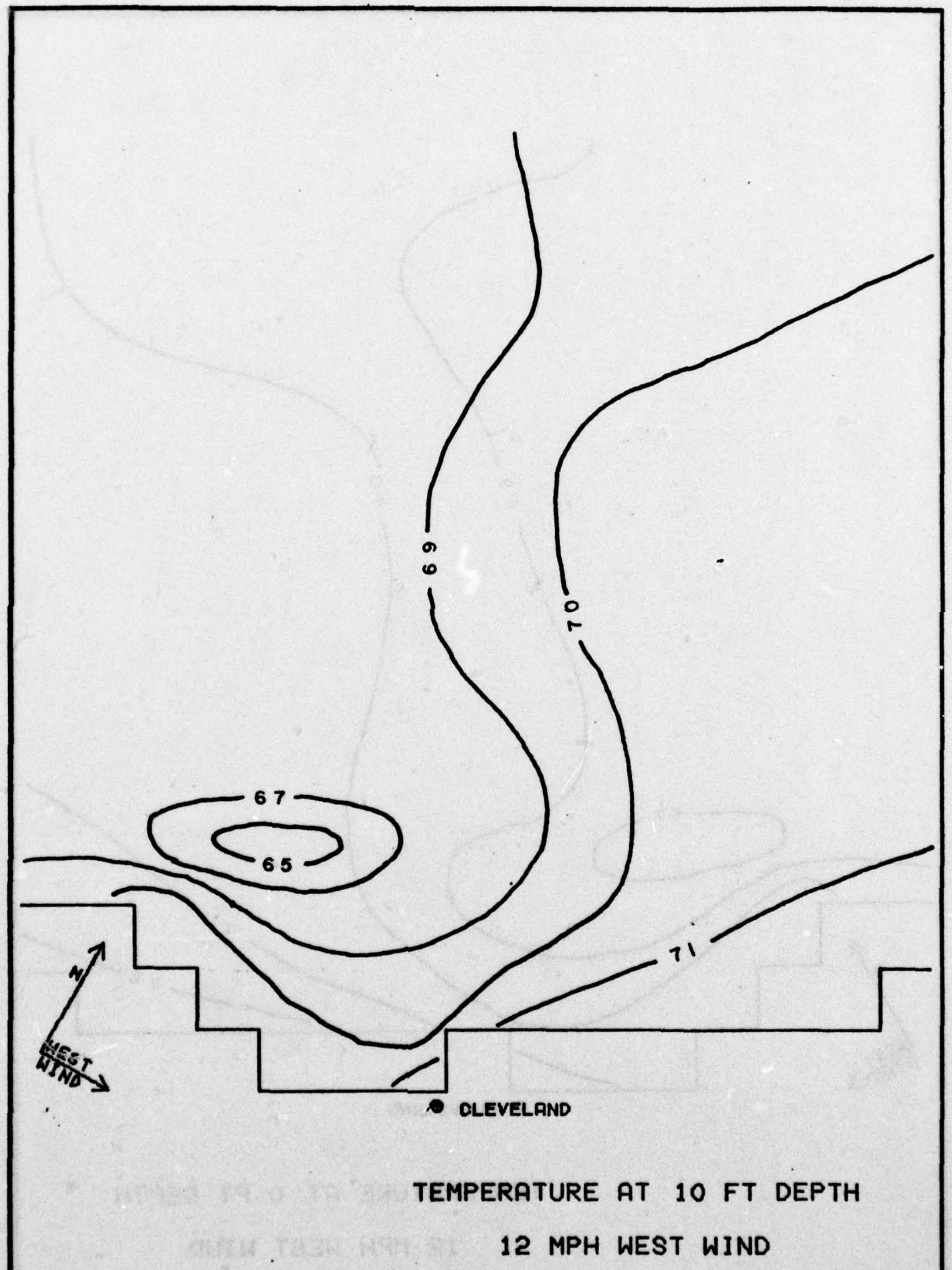


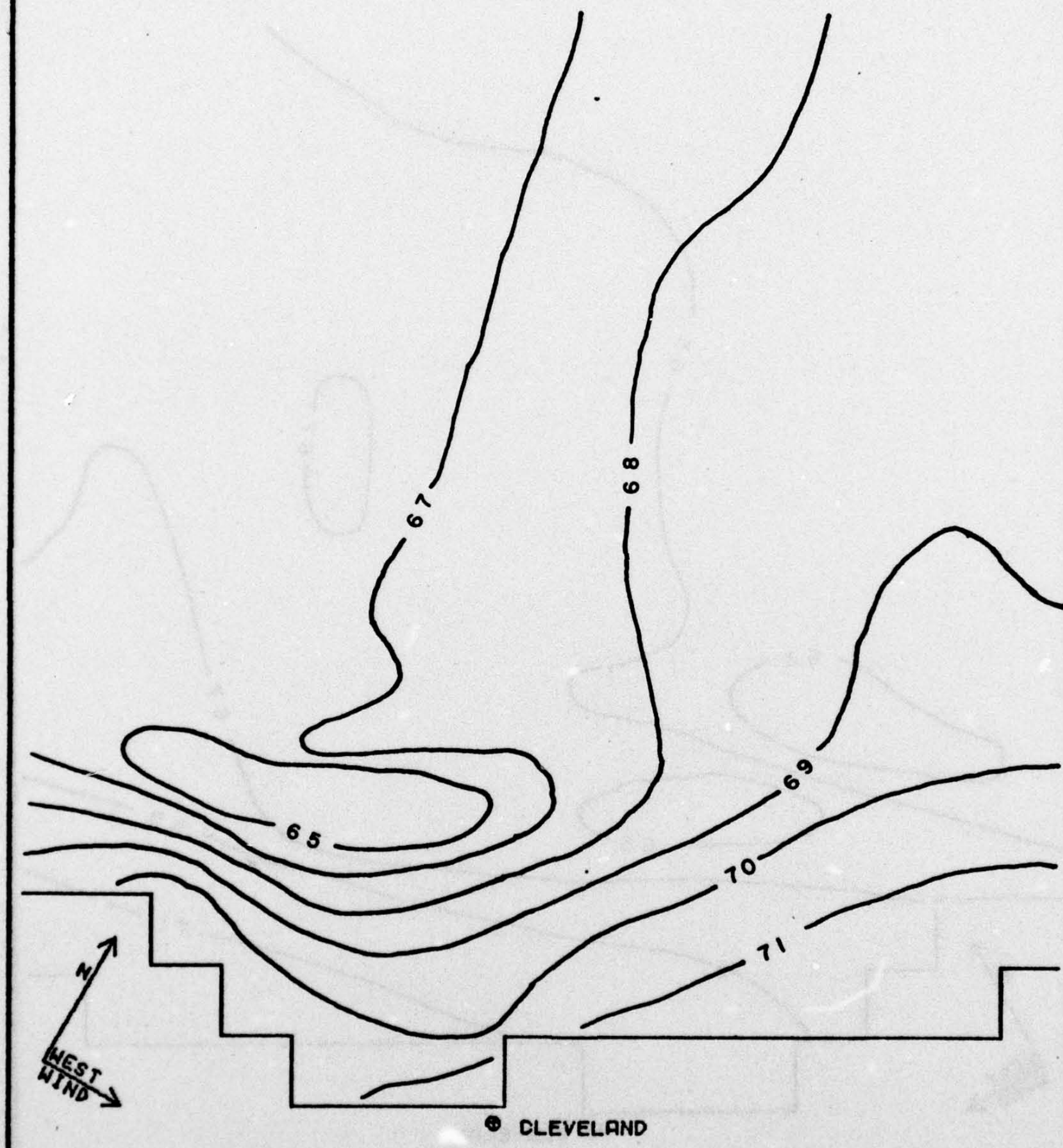
TEMPERATURE AT 0 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION WITHOUT JETPORT

PLATE 19


69
70
67
65
71
N
WEST WIND
CLEVELAND
TEMPERATURE AT 10 FT DEPTH
12 MPH WEST WIND
7.4 HRS SIMULATION WITHOUT JETPORT
PLATE 20

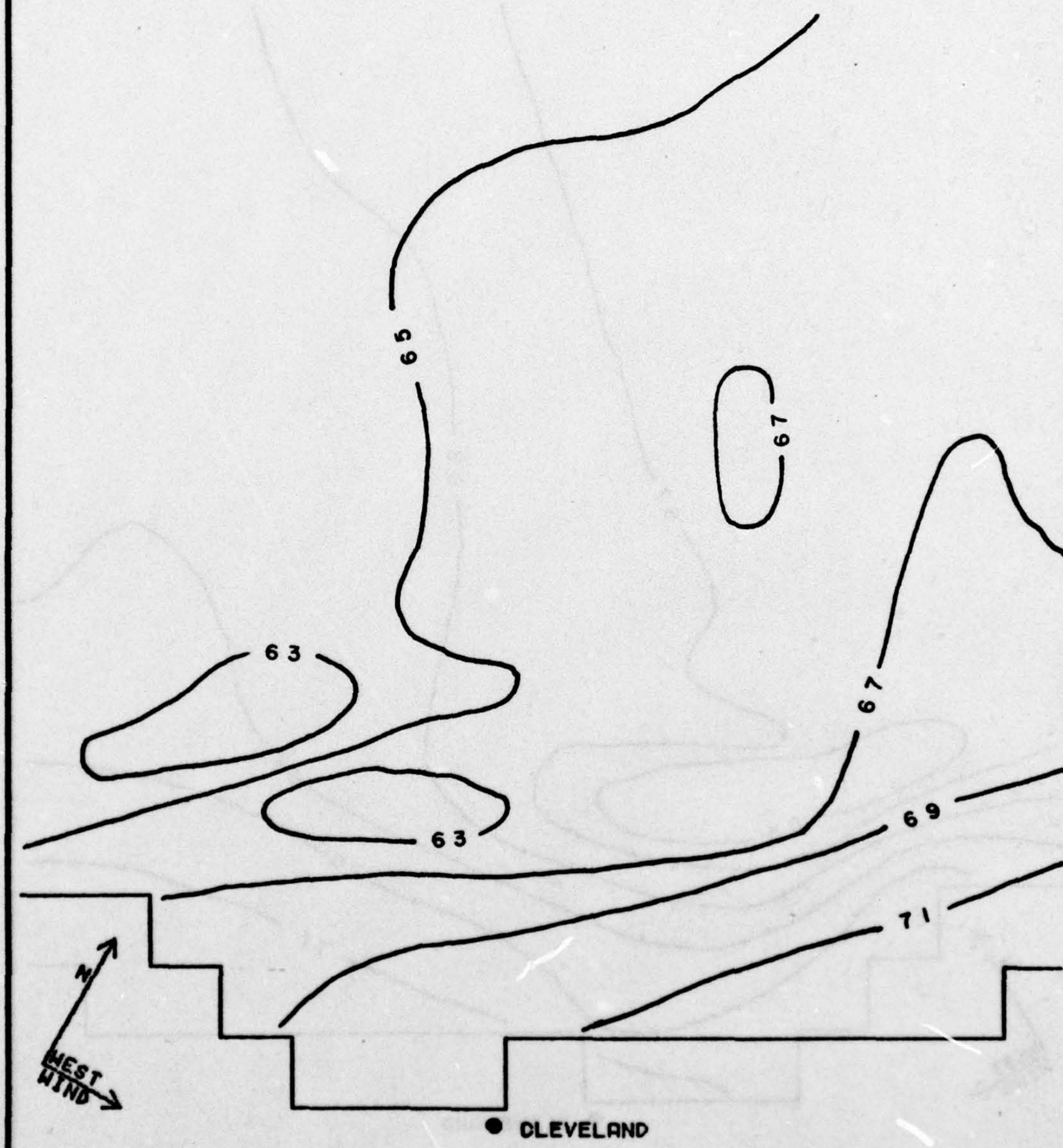


TEMPERATURE AT 15 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION WITHOUT JETPORT

PLATE 21

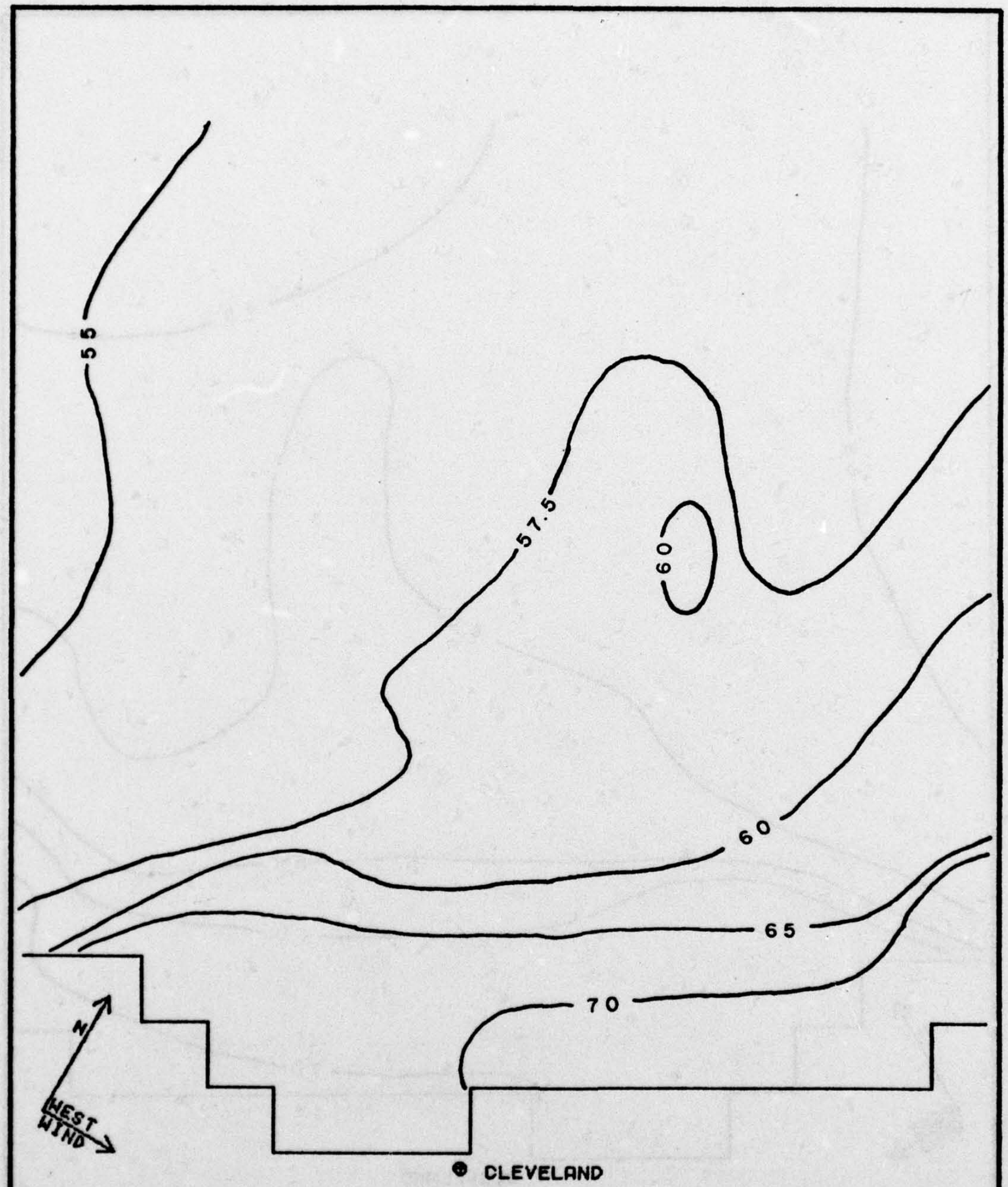


TEMPERATURE AT 20 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION WITHOUT JETPORT

PLATE 22

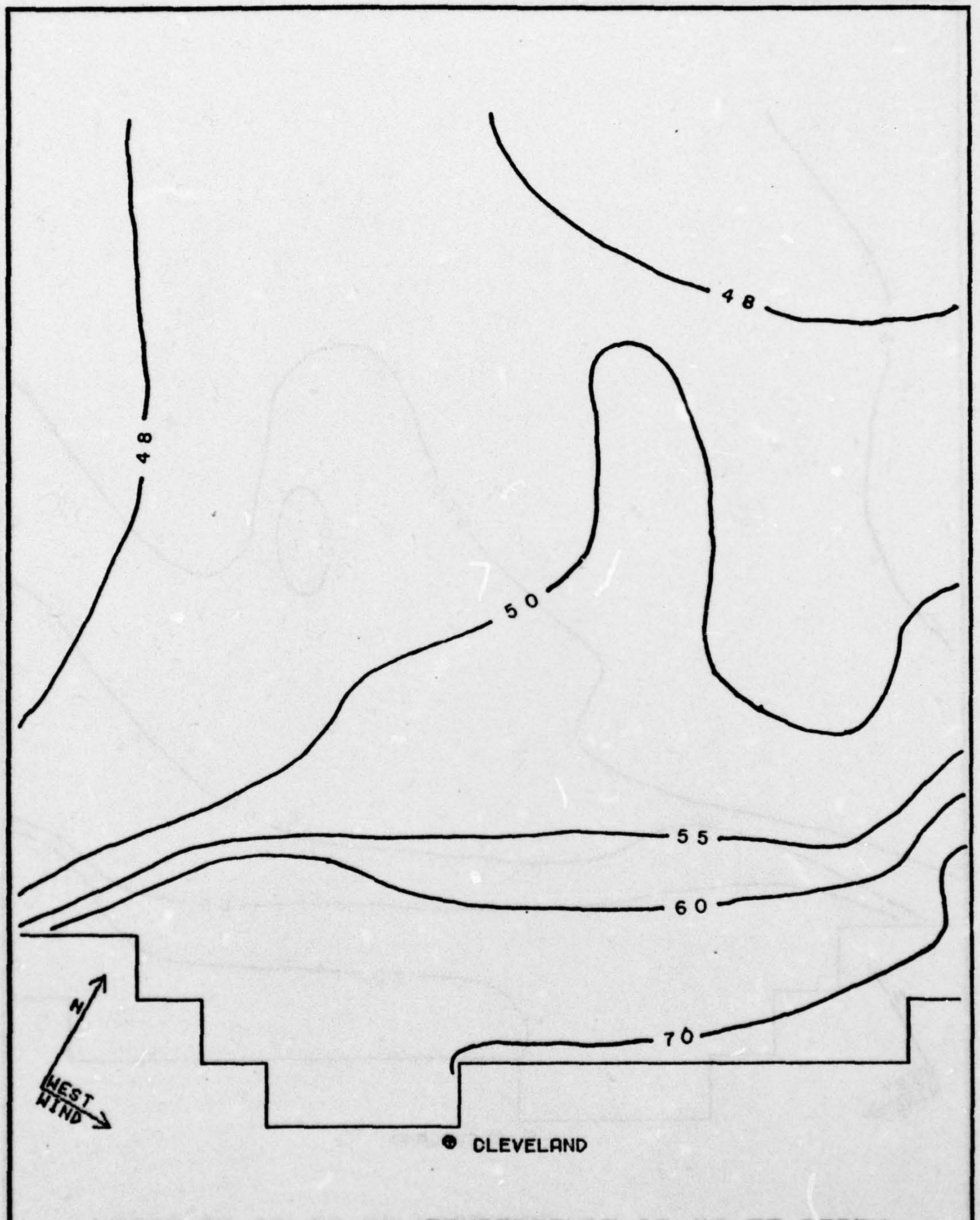


TEMPERATURE AT 30 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION WITHOUT JETPORT

PLATE 23

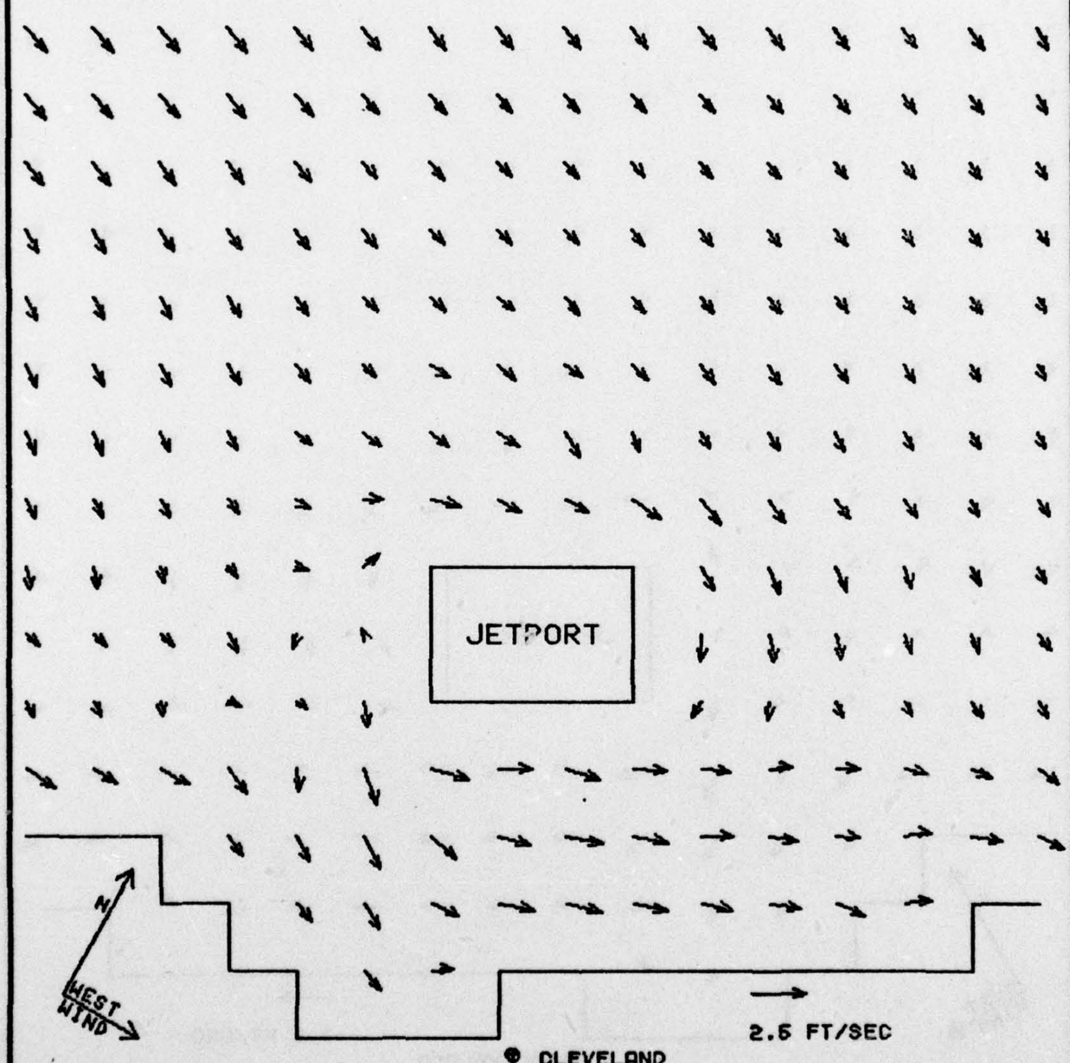


TEMPERATURE AT 40 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION WITHOUT JETPORT

PLATE 24



HORIZONTAL VELOCITY AT 0 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION WITH JETPORT

PLATE 25

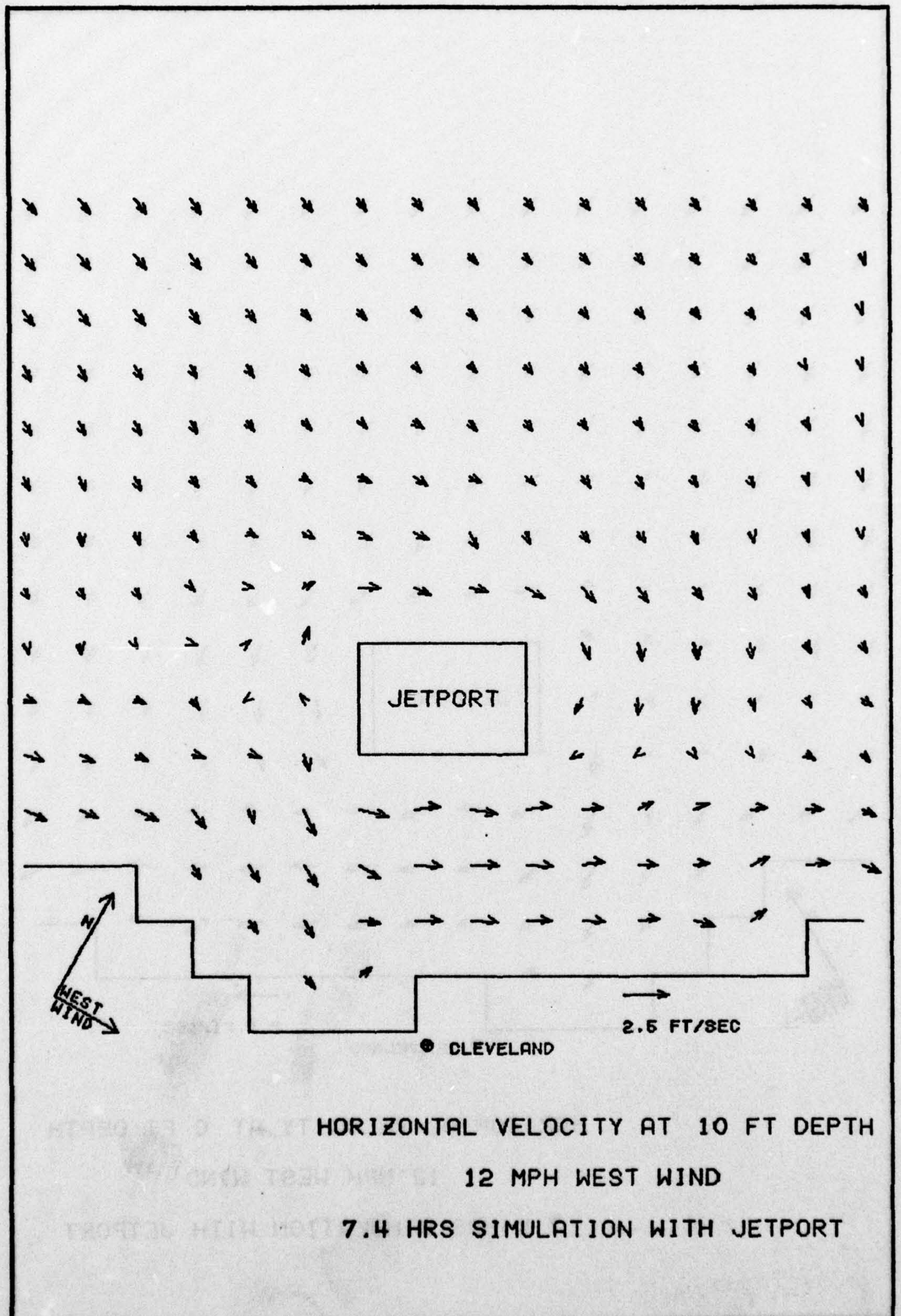
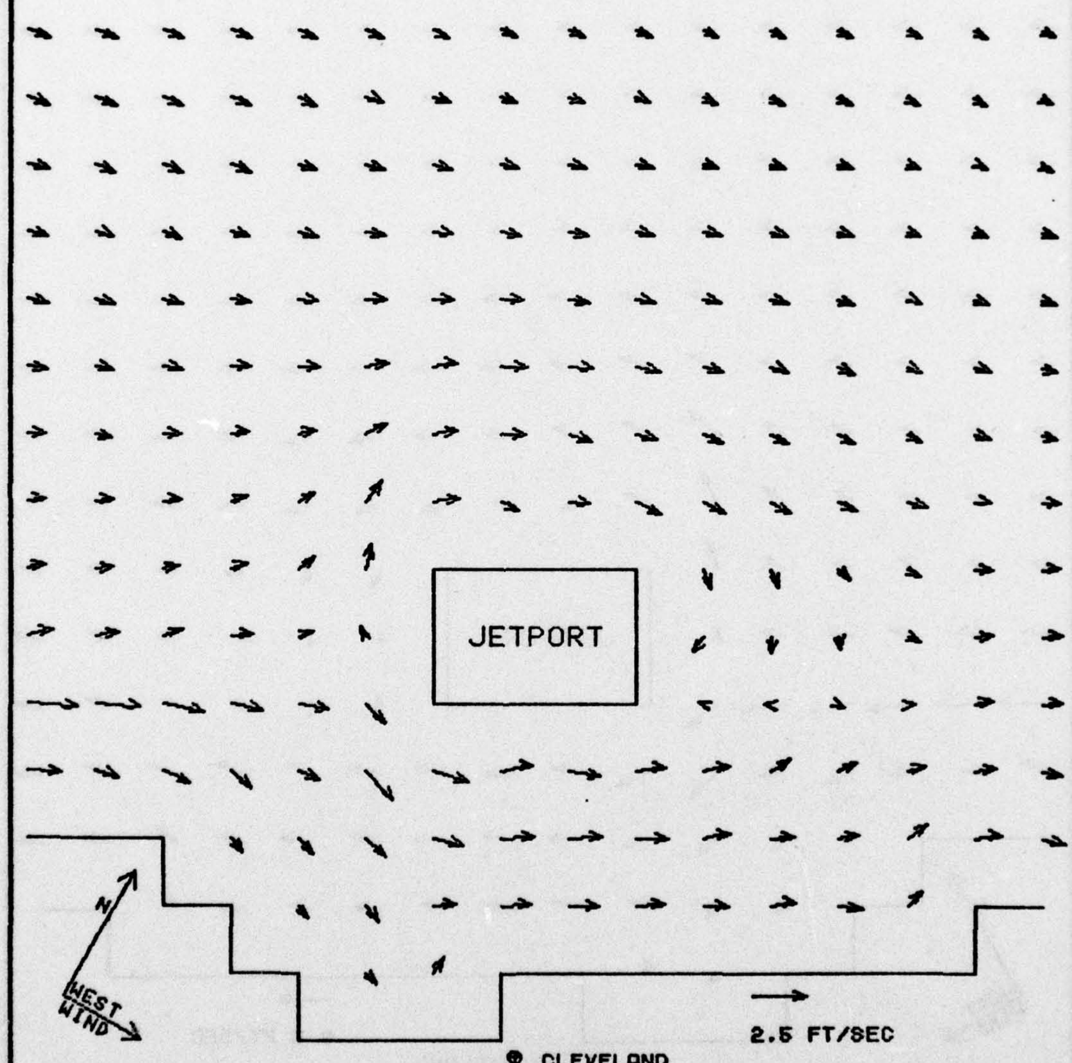

JETPORT
N
WEST WIND
2.5 FT/SEC
CLEVELAND
HORIZONTAL VELOCITY AT 10 FT DEPTH
12 MPH WEST WIND
7.4 HRS SIMULATION WITH JETPORT

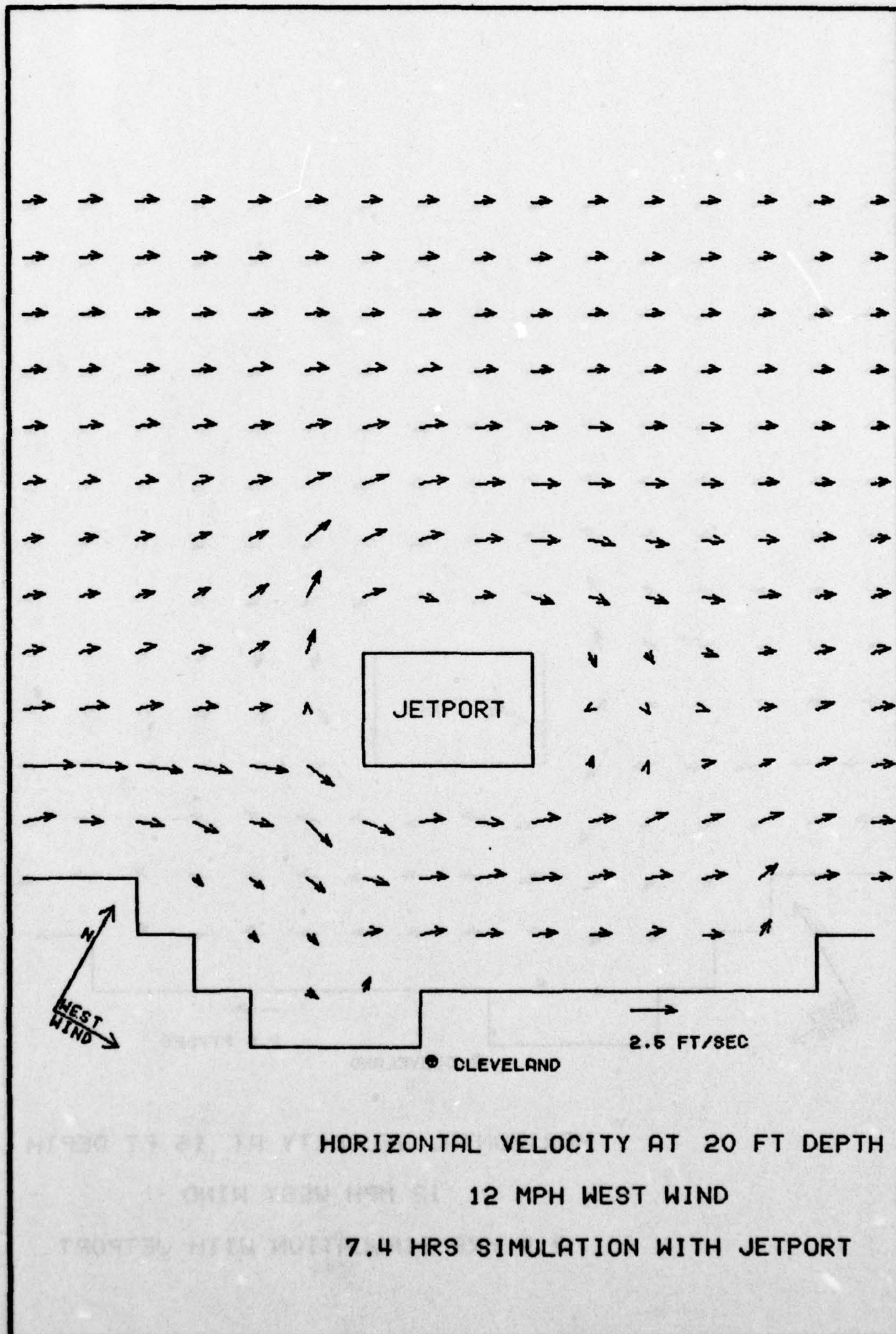
PLATE 26



HORIZONTAL VELOCITY AT 15 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION WITH JETPORT



JETPORT
N
WEST WIND
2.5 FT/SEC
CLEVELAND
HORIZONTAL VELOCITY AT 20 FT DEPTH
12 MPH WEST WIND
7.4 HRS SIMULATION WITH JETPORT

PLATE 28

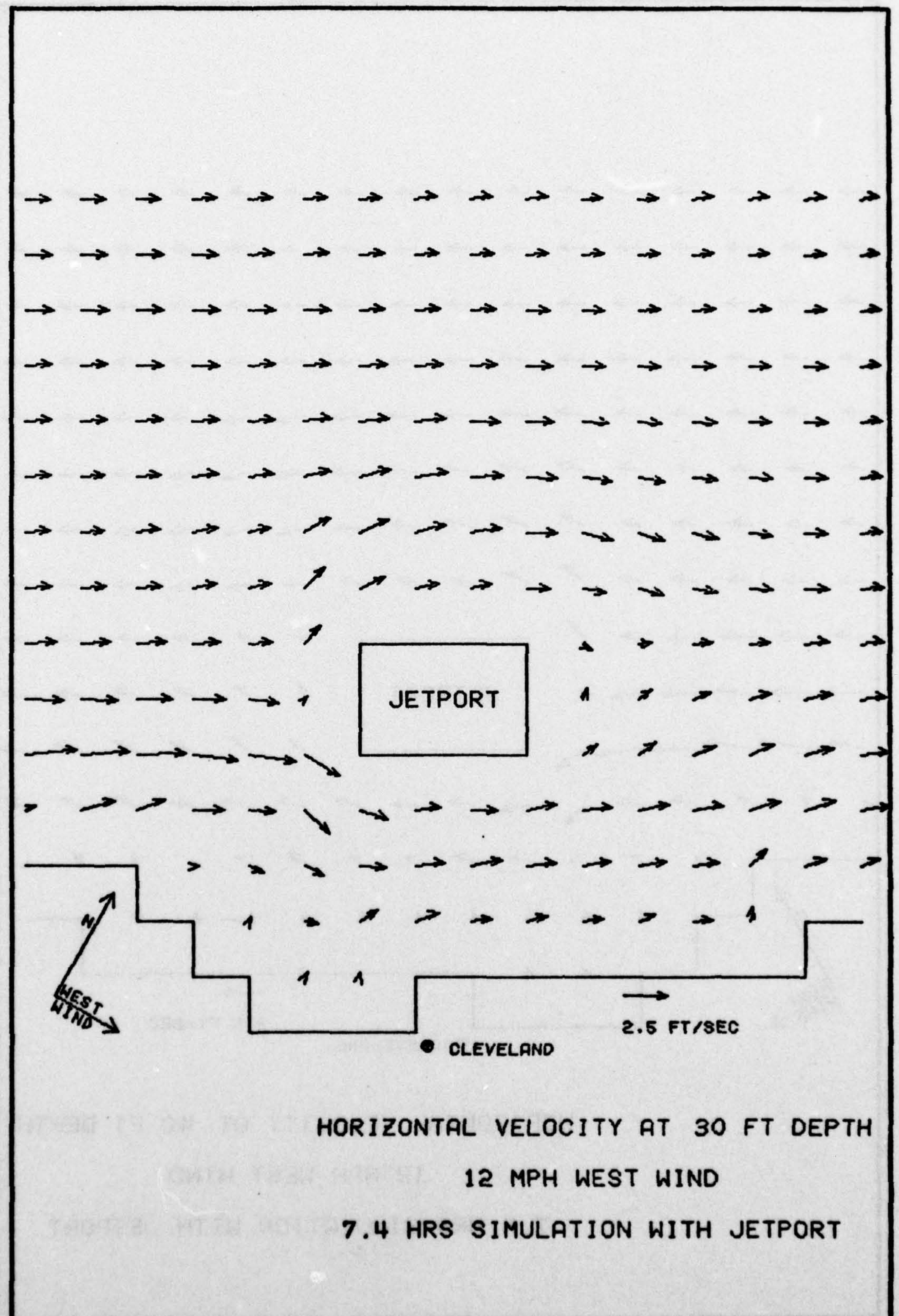

JETPORT
N
WEST
WIND
2.5 FT/SEC
CLEVELAND
HORIZONTAL VELOCITY AT 30 FT DEPTH
12 MPH WEST WIND
7.4 HRS SIMULATION WITH JETPORT

PLATE 29

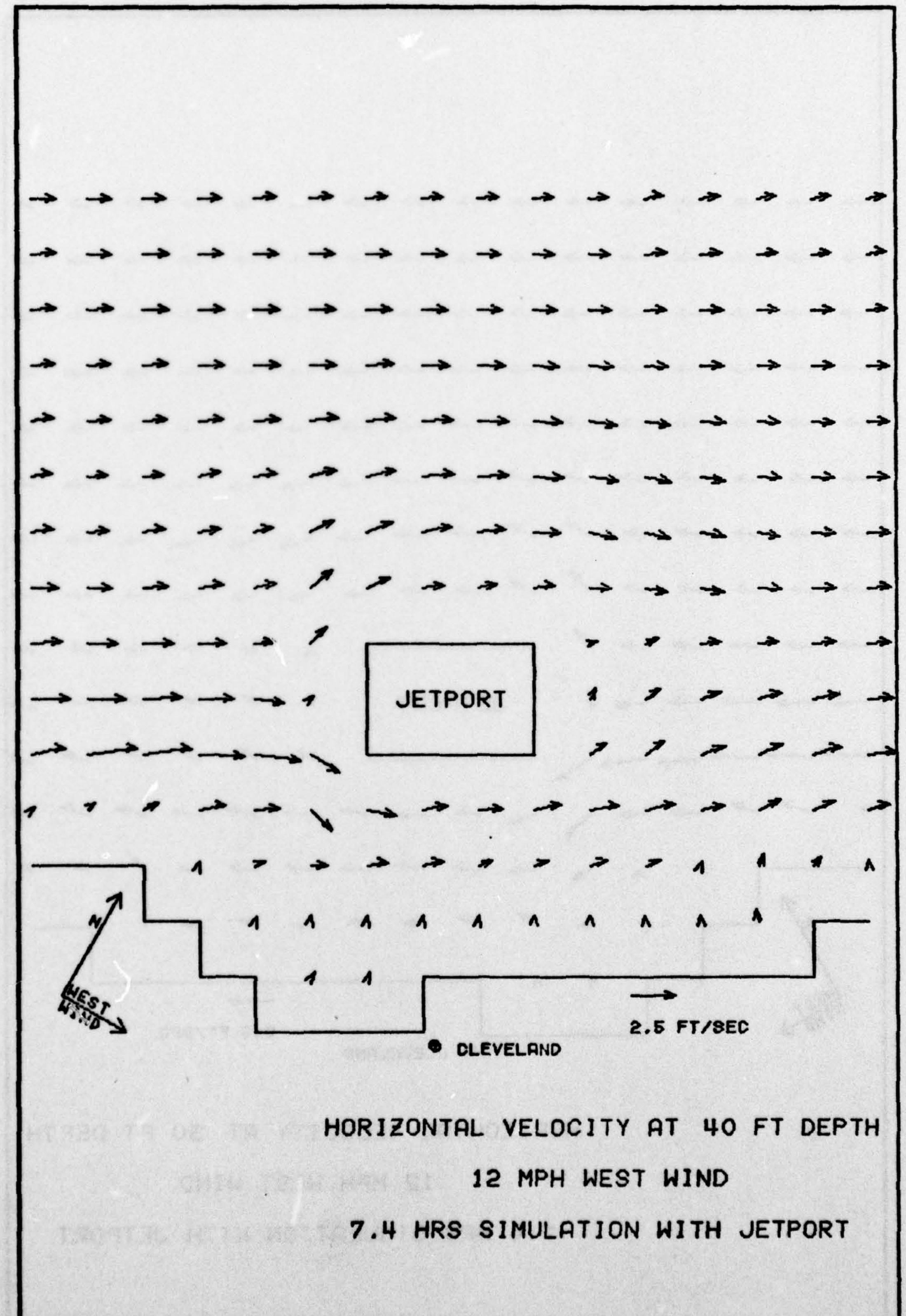

JETPORT
N
WEST WIND
2.5 FT/SEC
CLEVELAND
HORIZONTAL VELOCITY AT 40 FT DEPTH
12 MPH WEST WIND
7.4 HRS SIMULATION WITH JETPORT

PLATE 30

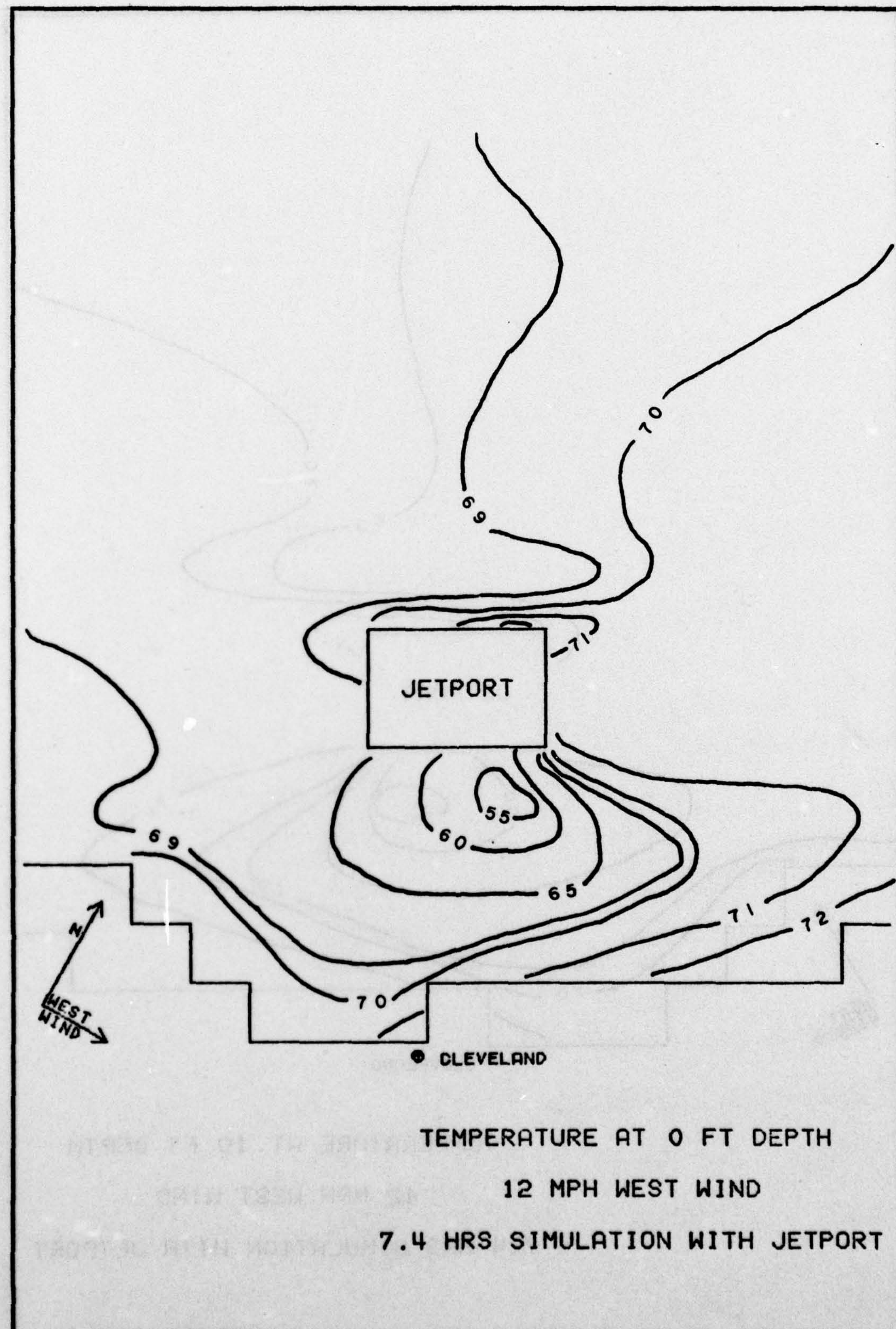
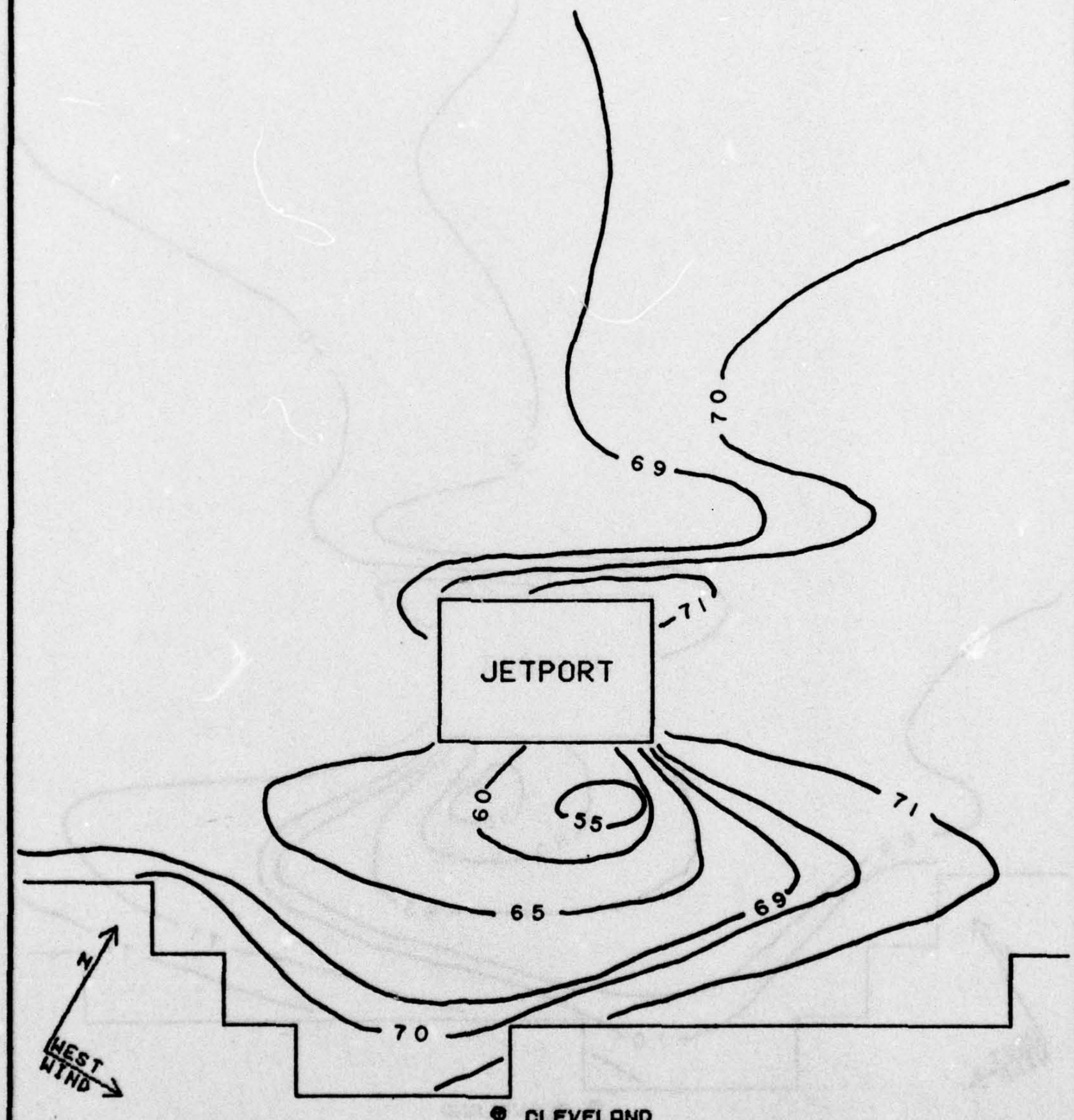

JETPORT
70
69
71
55
60
65
69
70
71
72
N
WEST WIND
CLEVELAND
TEMPERATURE AT 0 FT DEPTH
12 MPH WEST WIND
7.4 HRS SIMULATION WITH JETPORT

PLATE 31

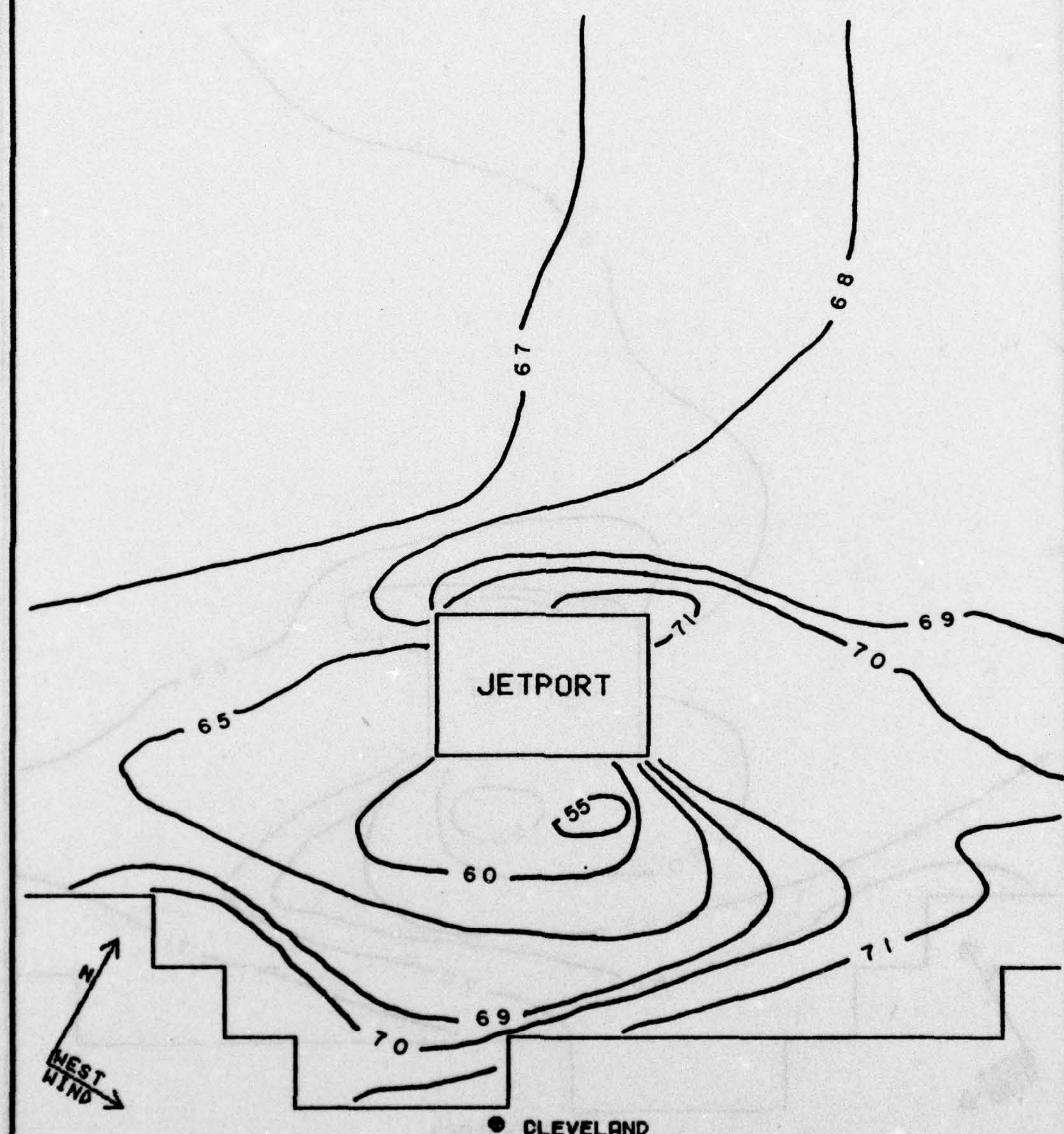


TEMPERATURE AT 10 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION WITH JETPORT

PLATE 32



TEMPERATURE AT 15 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION WITH JETPORT

PLATE 33

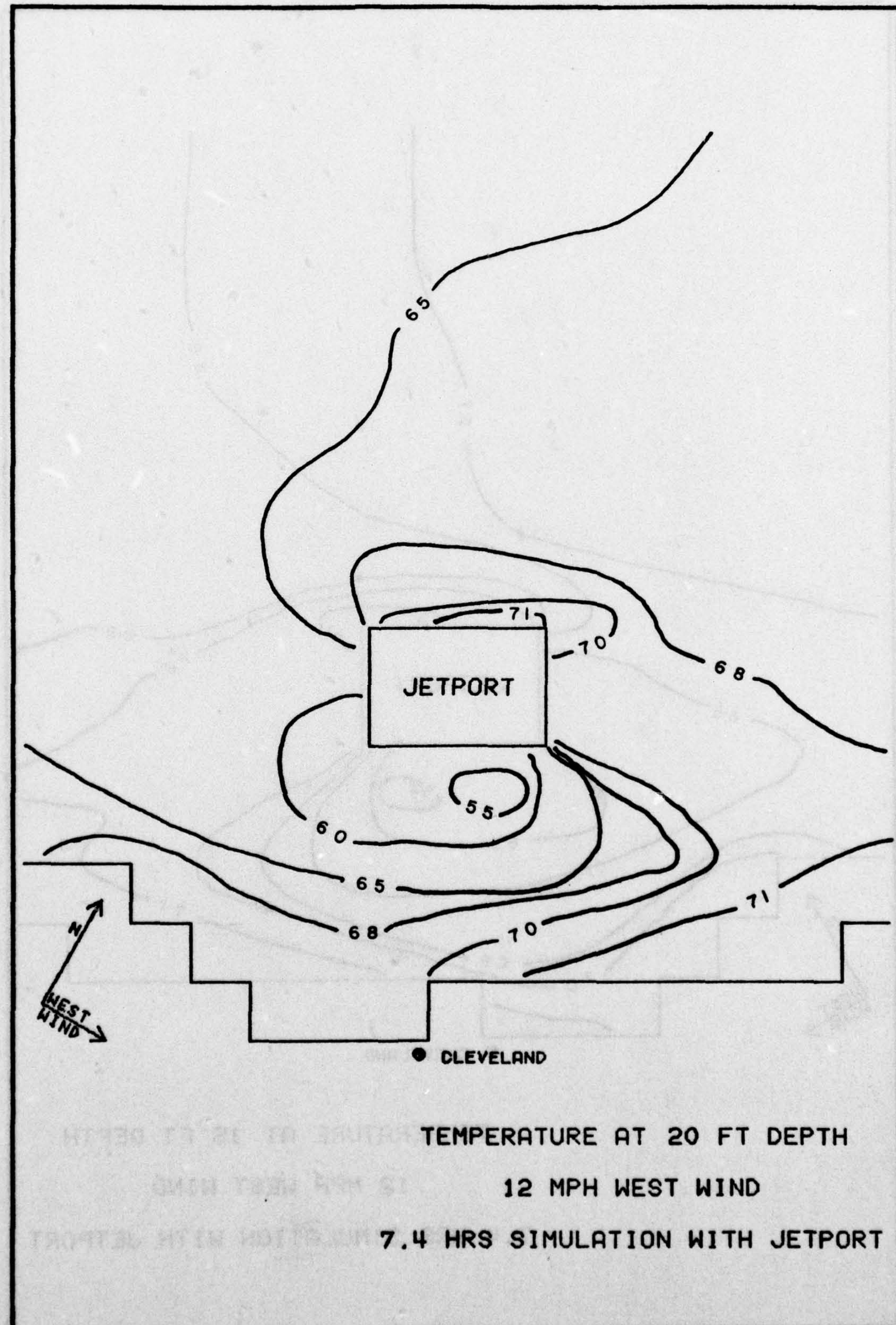
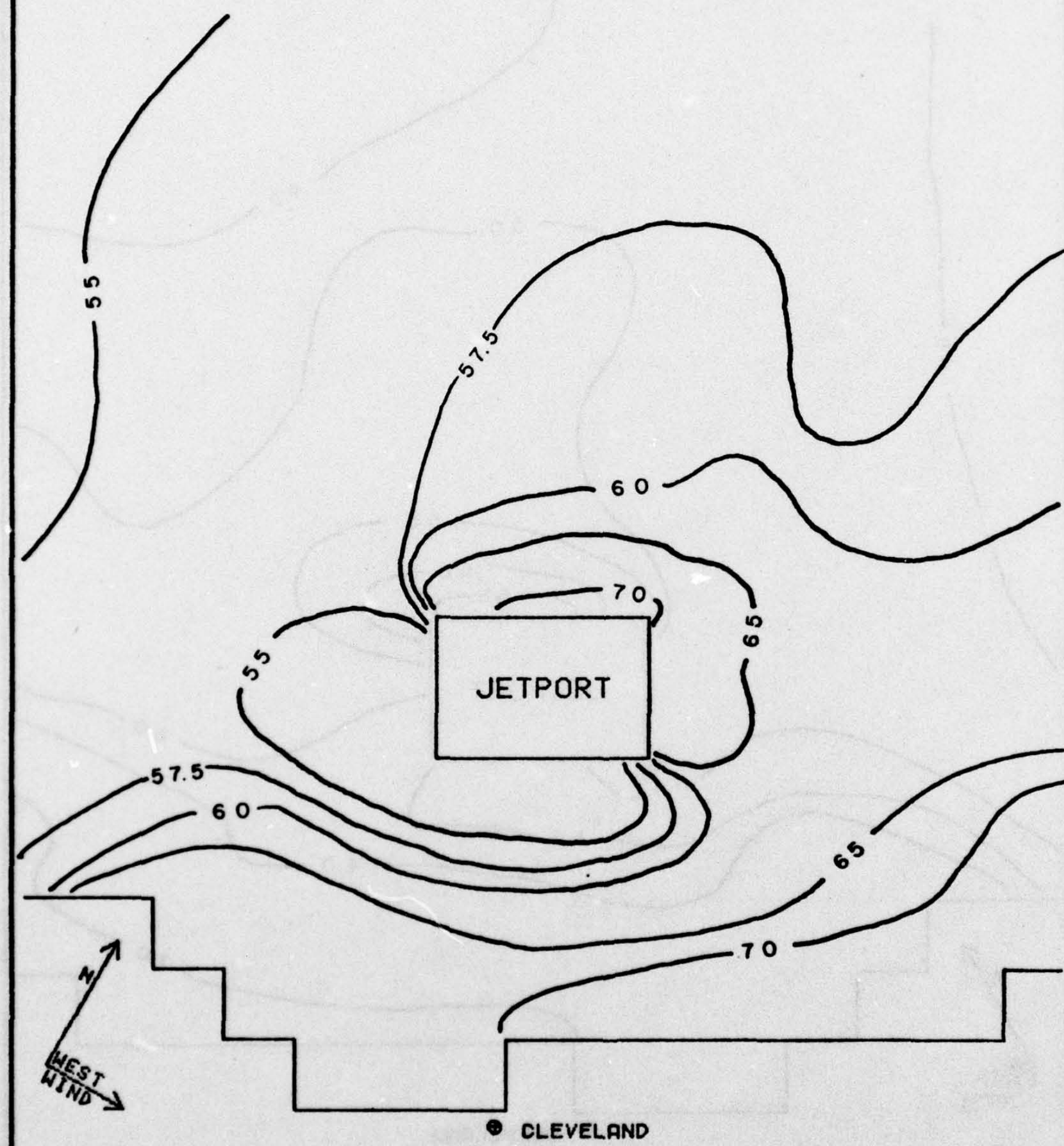

65
71
70
68
JETPORT
55
60
65
68
70
71
N
WEST WIND
CLEVELAND
TEMPERATURE AT 20 FT DEPTH
12 MPH WEST WIND
7.4 HRS SIMULATION WITH JETPORT

PLATE 34



TEMPERATURE AT 30 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION WITH JETPORT

PLATE 35

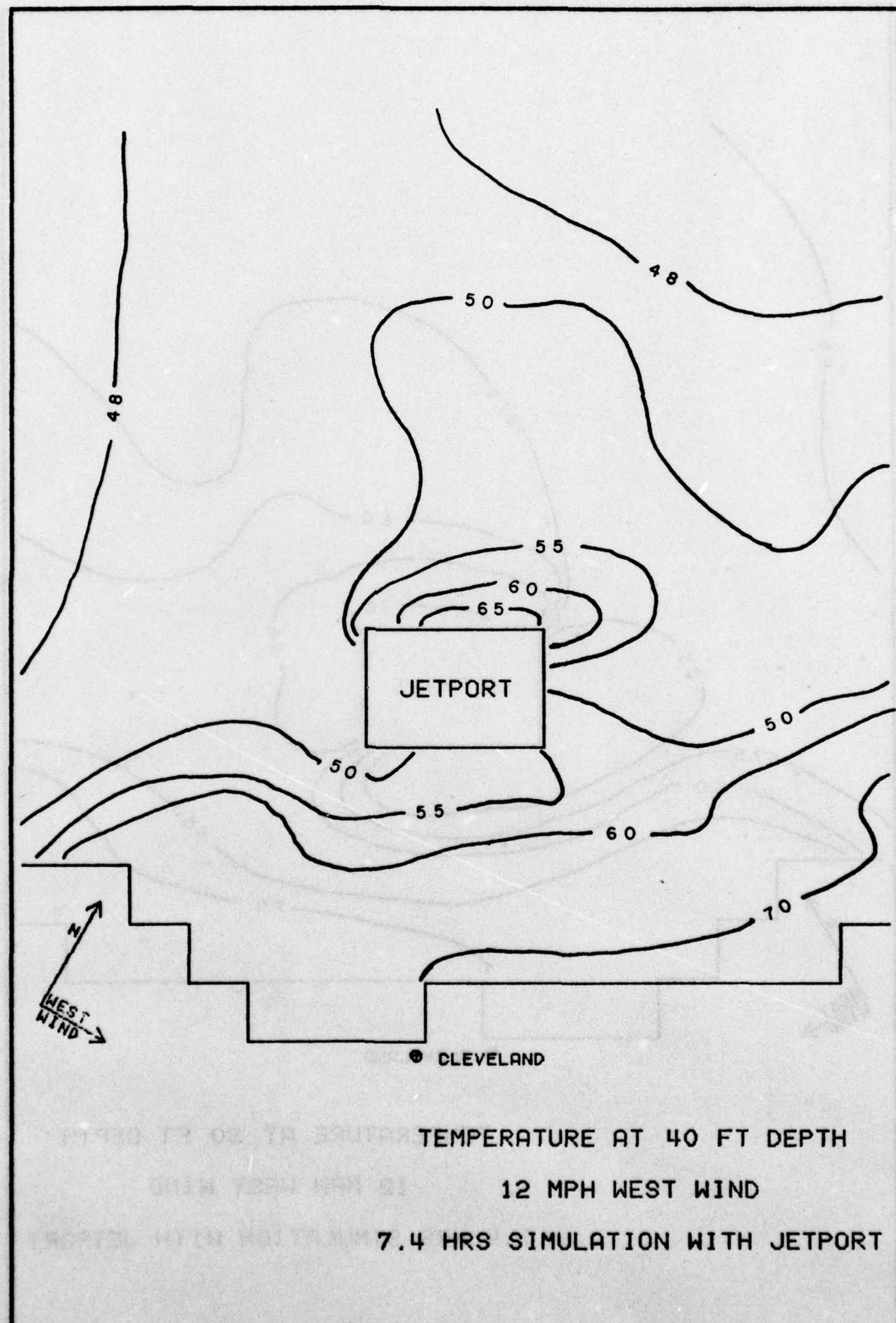

48
48
50
55
60
65
JETPORT
50
50
55
60
70
N
WEST WIND
CLEVELAND
TEMPERATURE AT 40 FT DEPTH
12 MPH WEST WIND
7.4 HRS SIMULATION WITH JETPORT

PLATE 36

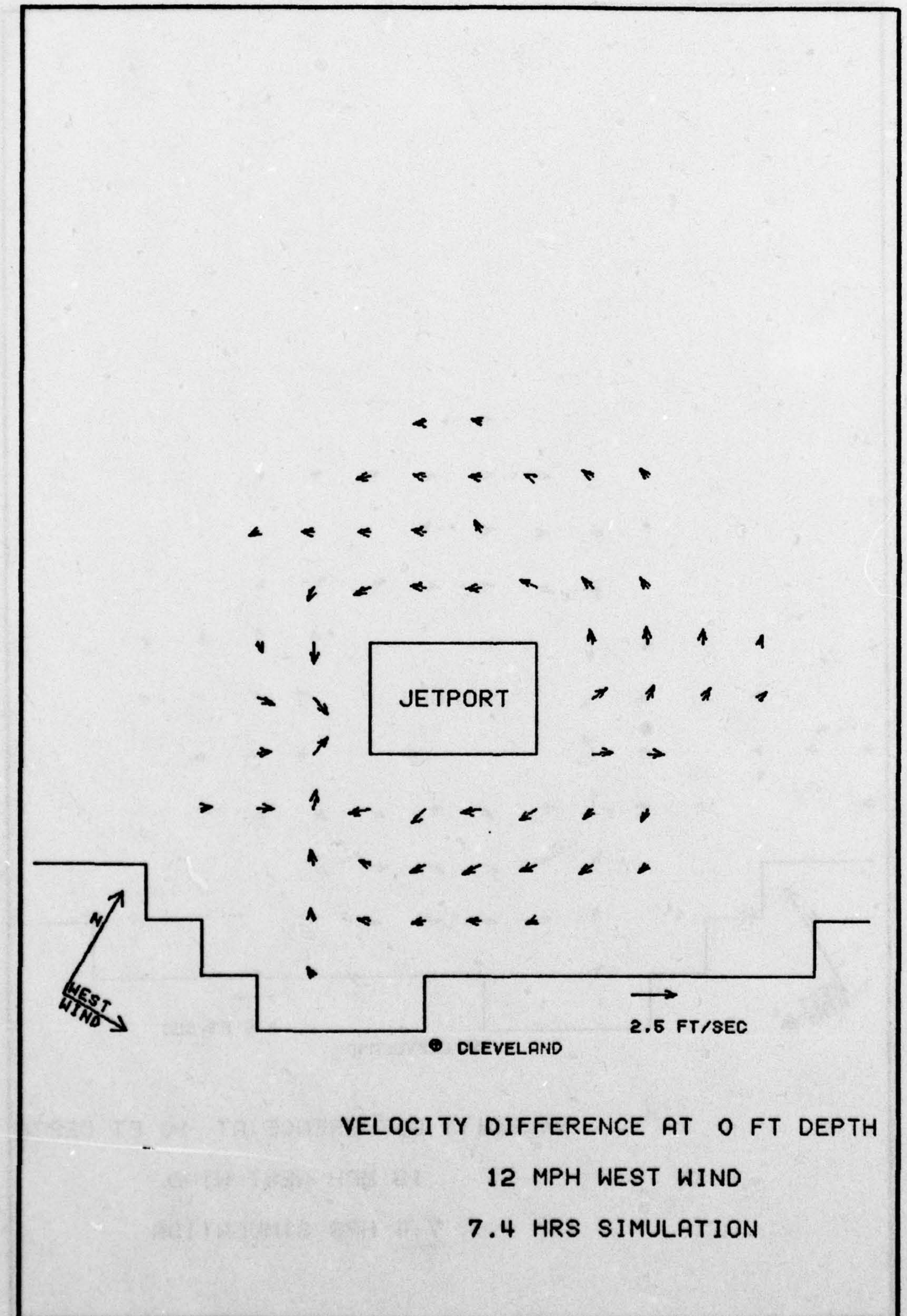

JETPORT
N
WEST WIND
2.5 FT/SEC
CLEVELAND
VELOCITY DIFFERENCE AT 0 FT DEPTH
12 MPH WEST WIND
7.4 HRS SIMULATION

PLATE 37

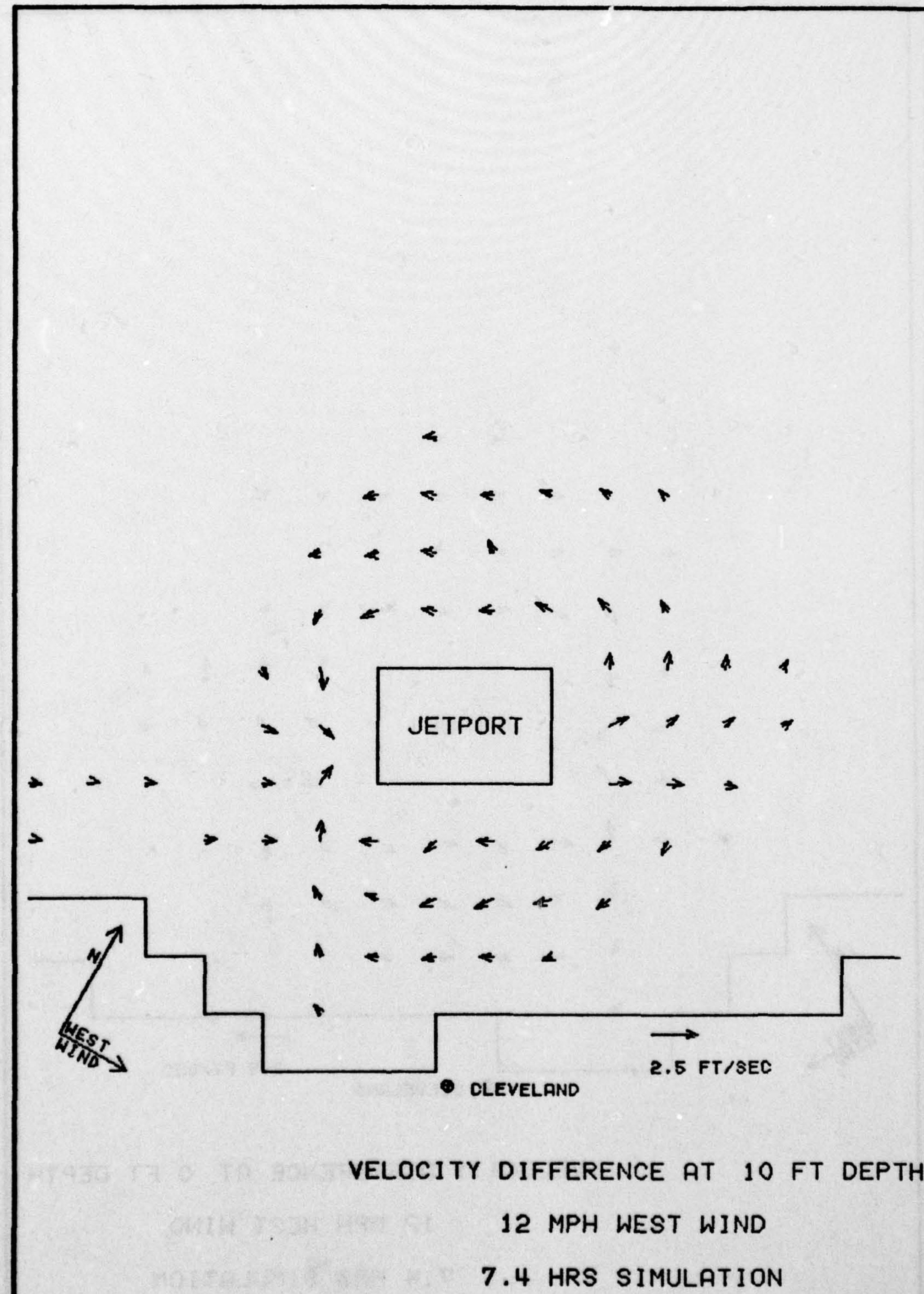
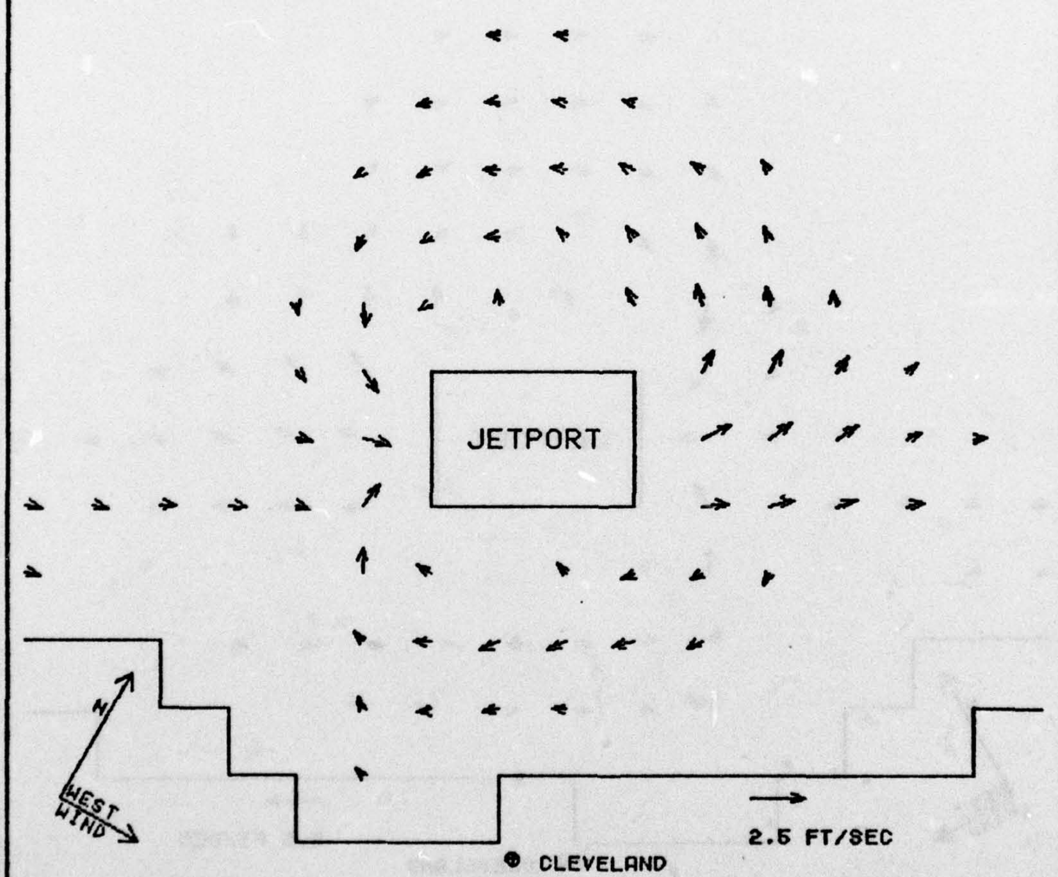

JETPORT
N
WEST WIND
2.5 FT/SEC
CLEVELAND
VELOCITY DIFFERENCE AT 10 FT DEPTH
12 MPH WEST WIND
7.4 HRS SIMULATION

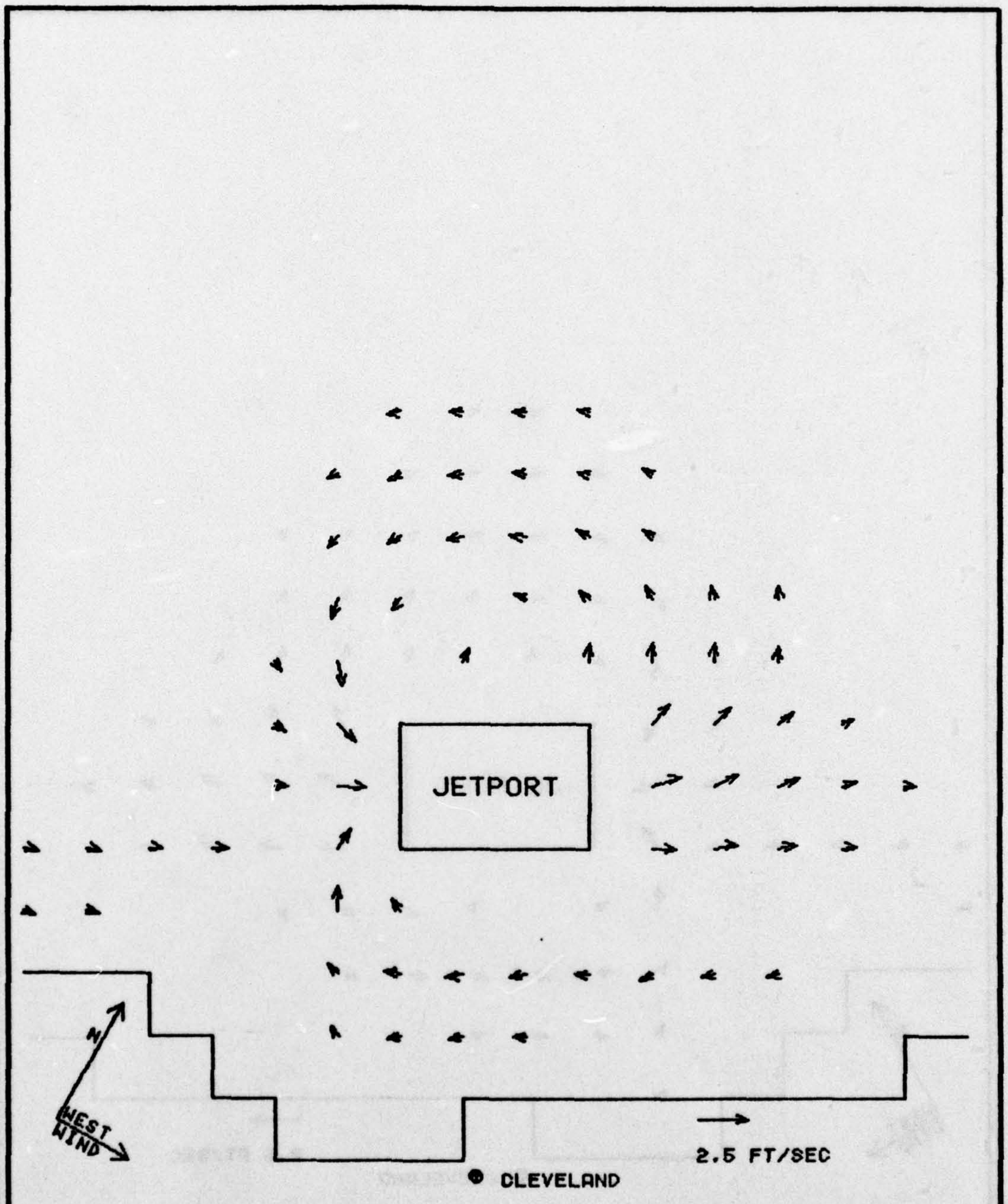
PLATE 38



VELOCITY DIFFERENCE AT 15 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION



VELOCITY DIFFERENCE AT 20 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION

PLATE 40

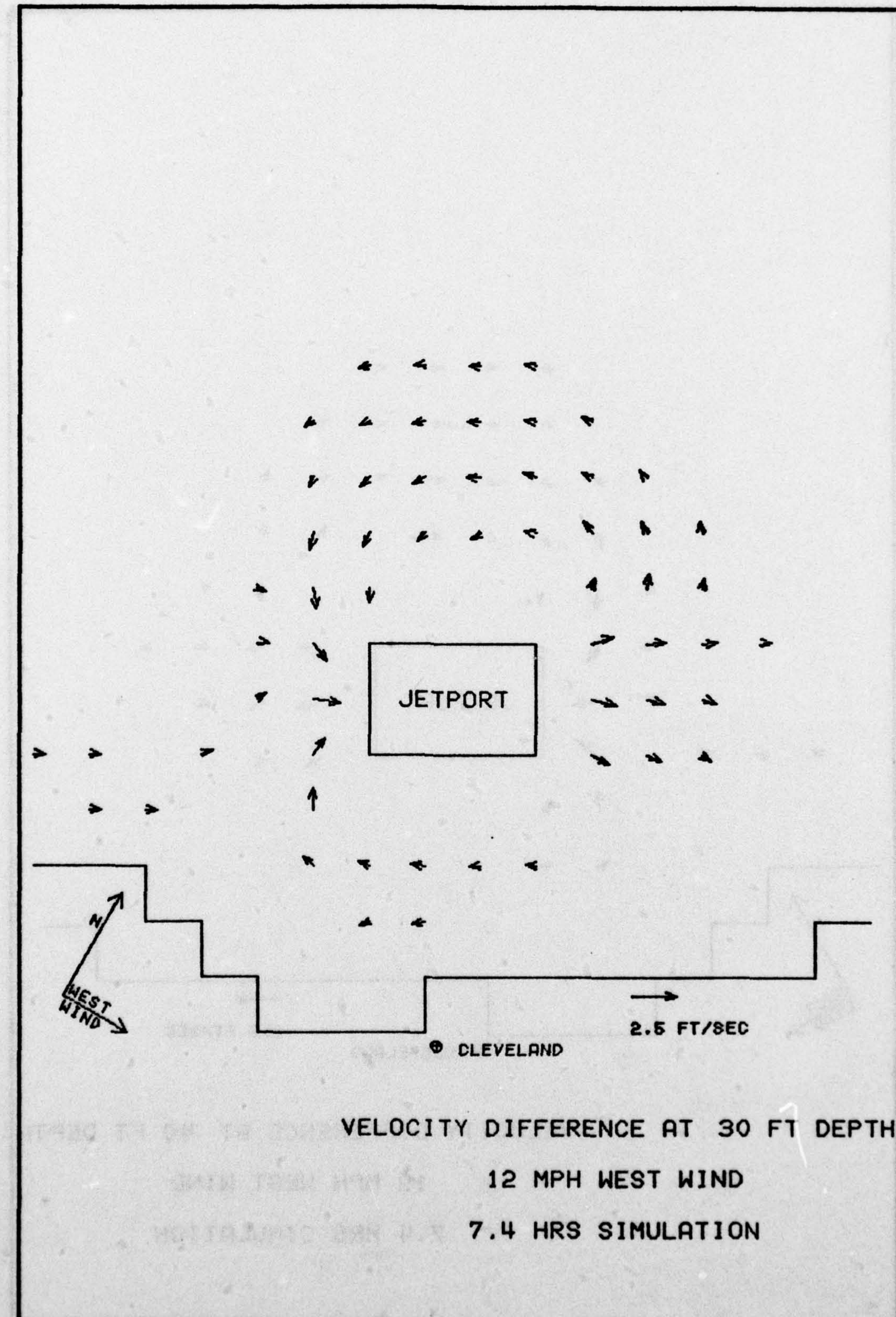

JETPORT
N
WEST WIND
2.5 FT/SEC
CLEVELAND
VELOCITY DIFFERENCE AT 30 FT DEPTH
12 MPH WEST WIND
7.4 HRS SIMULATION

PLATE 41

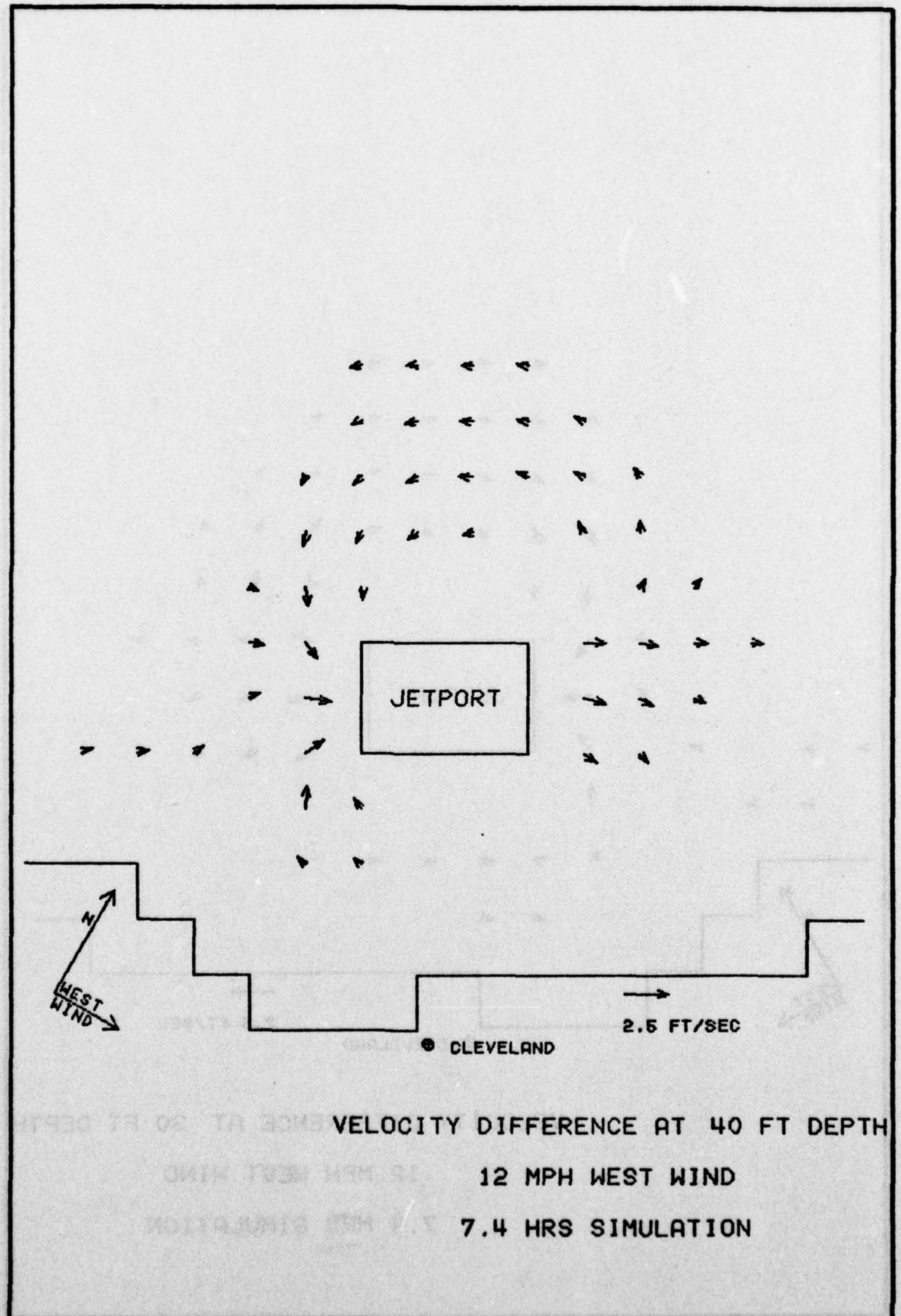
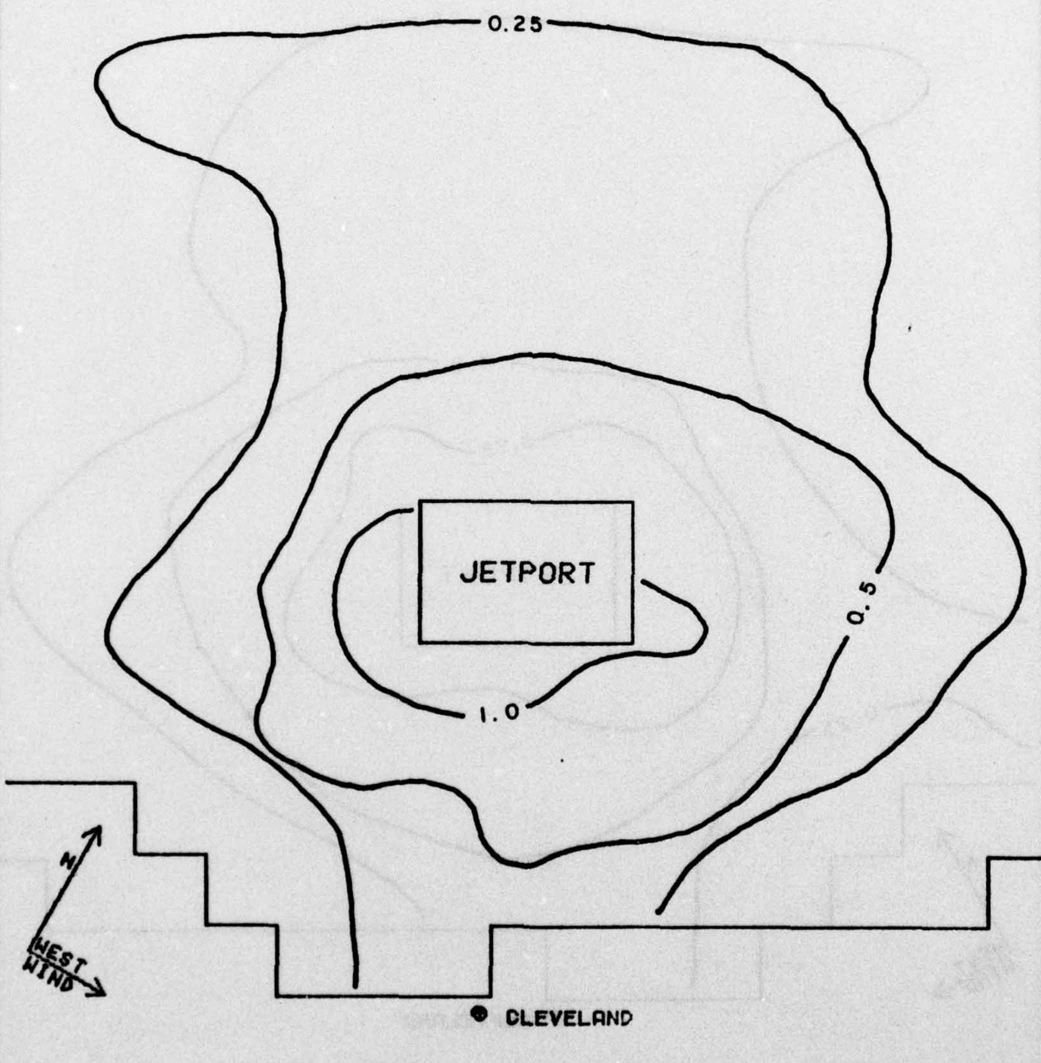

JETPORT
N
WEST WIND
2.5 FT/SEC
CLEVELAND
VELOCITY DIFFERENCE AT 40 FT DEPTH
12 MPH WEST WIND
7.4 HRS SIMULATION

PLATE 42

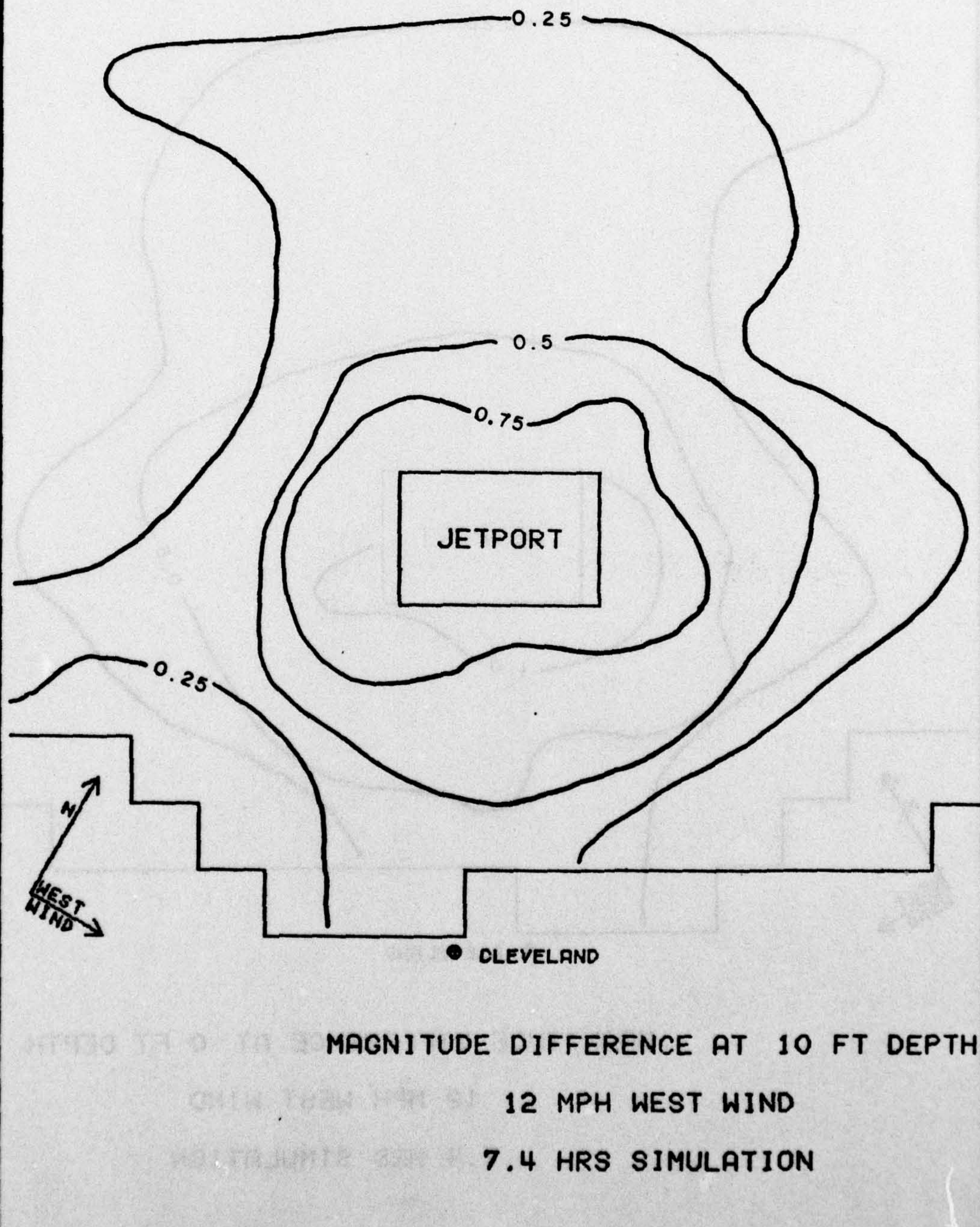


MAGNITUDE DIFFERENCE AT 0 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION

PLATE 43

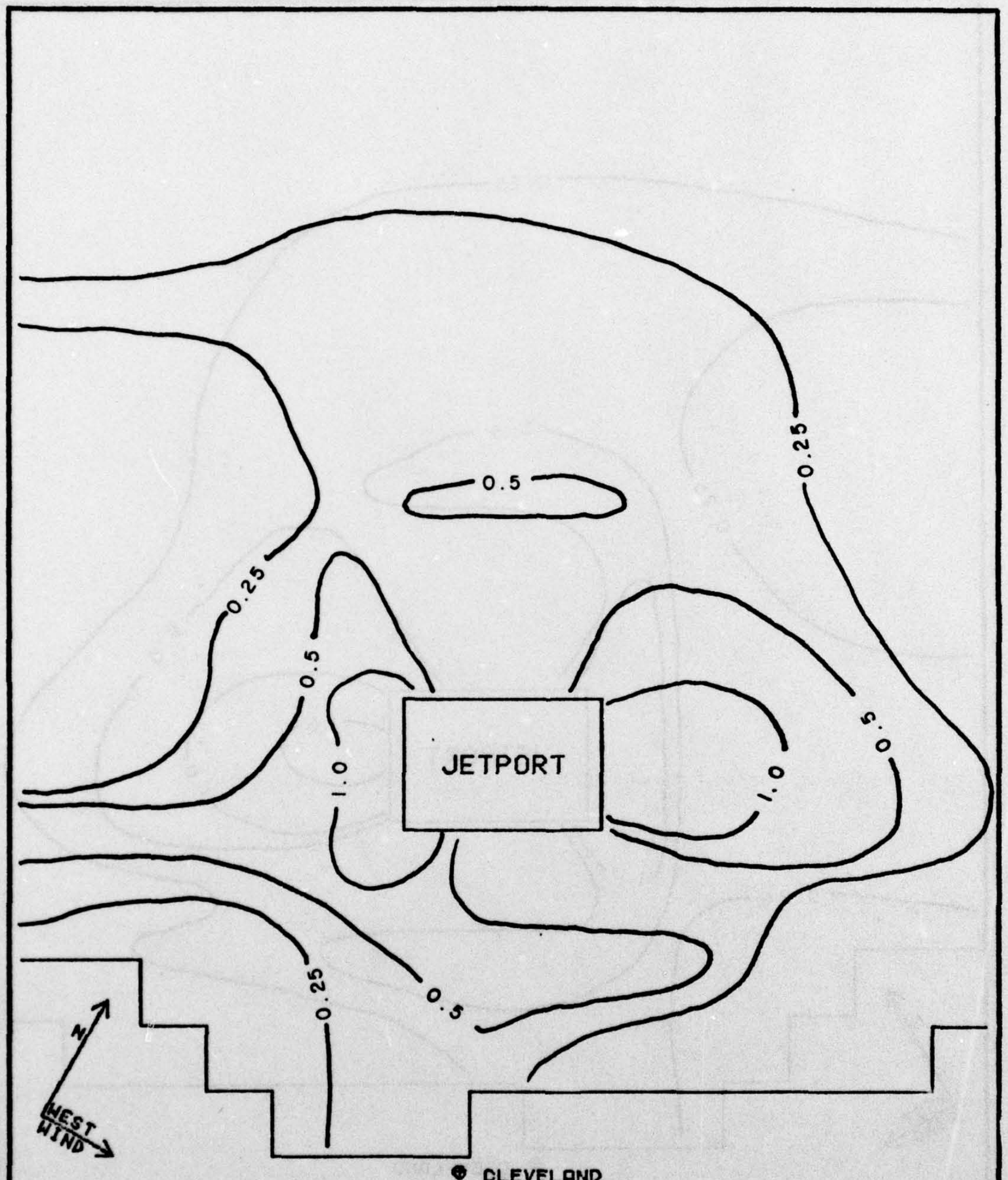


MAGNITUDE DIFFERENCE AT 10 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION

PLATE 44



MAGNITUDE DIFFERENCE AT 15 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION

PLATE 45

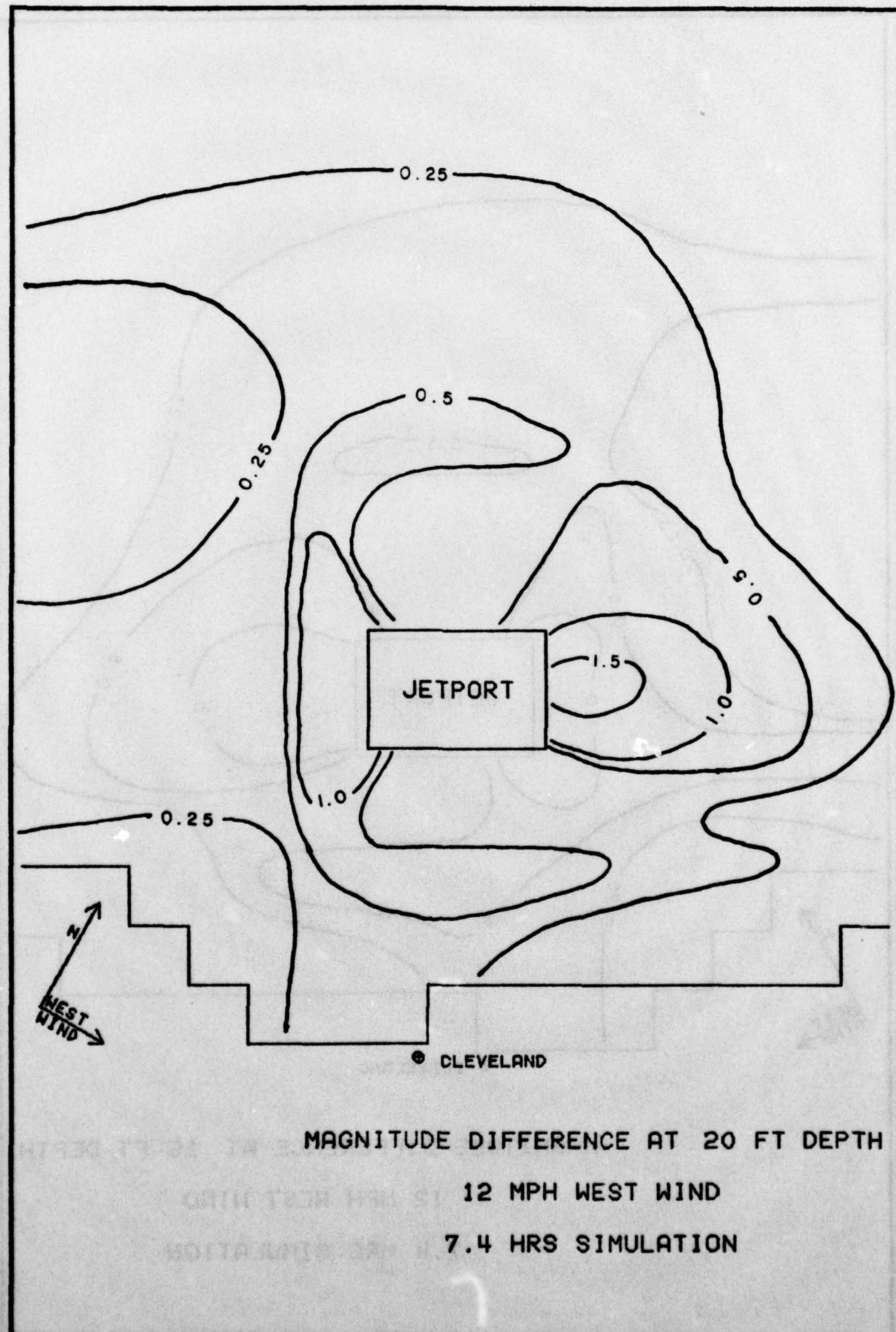
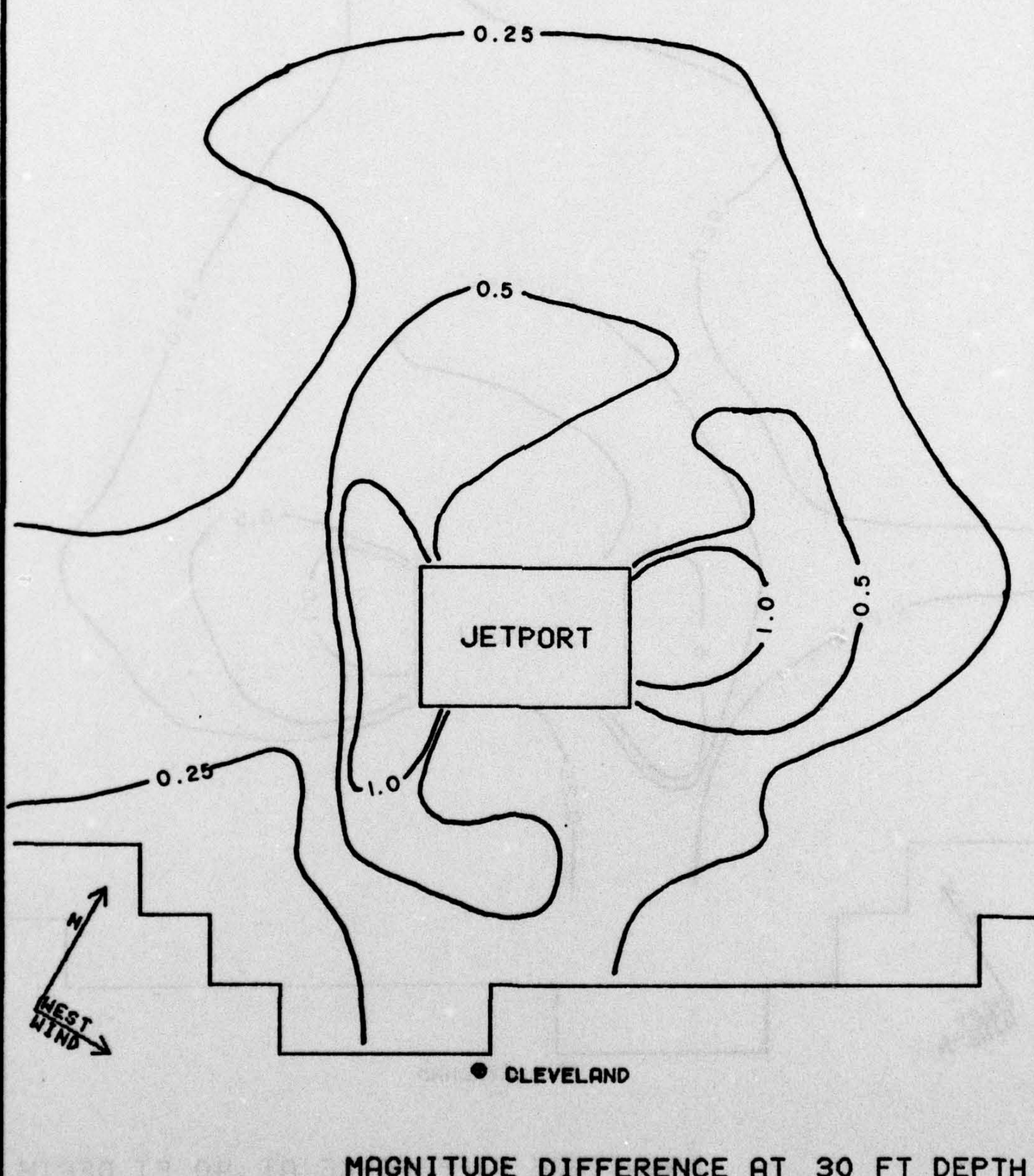
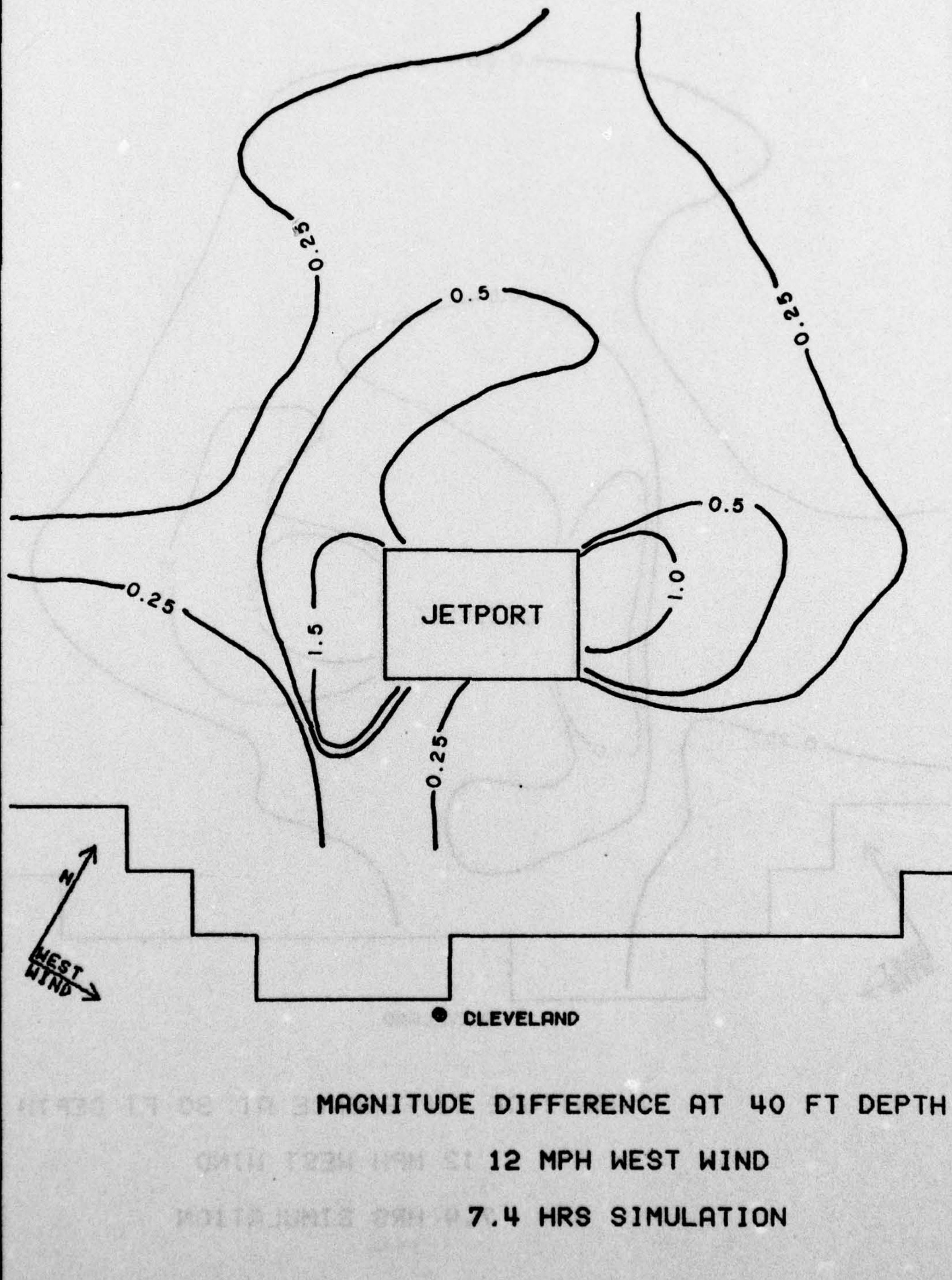

0.25
0.25
0.5
0.5
1.5
1.0
JETPORT
1.0
0.25
N
WEST WIND
CLEVELAND
MAGNITUDE DIFFERENCE AT 20 FT DEPTH
12 MPH WEST WIND
7.4 HRS SIMULATION

PLATE 46



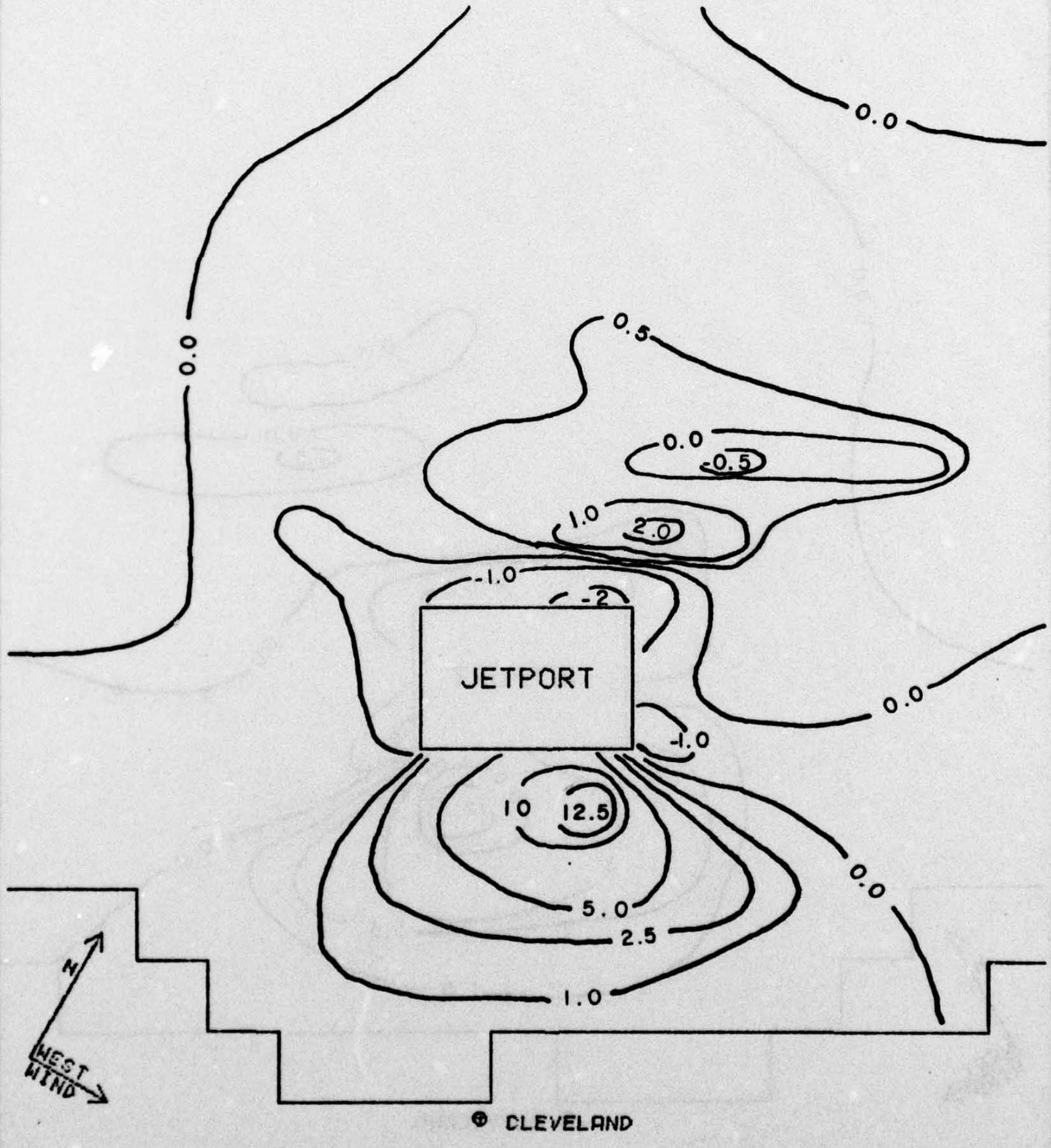
MAGNITUDE DIFFERENCE AT 30 FT DEPTH
12 MPH WEST WIND
7.4 HRS SIMULATION

PLATE 47



MAGNITUDE DIFFERENCE AT 40 FT DEPTH
12 MPH WEST WIND
7.4 HRS SIMULATION

PLATE 48

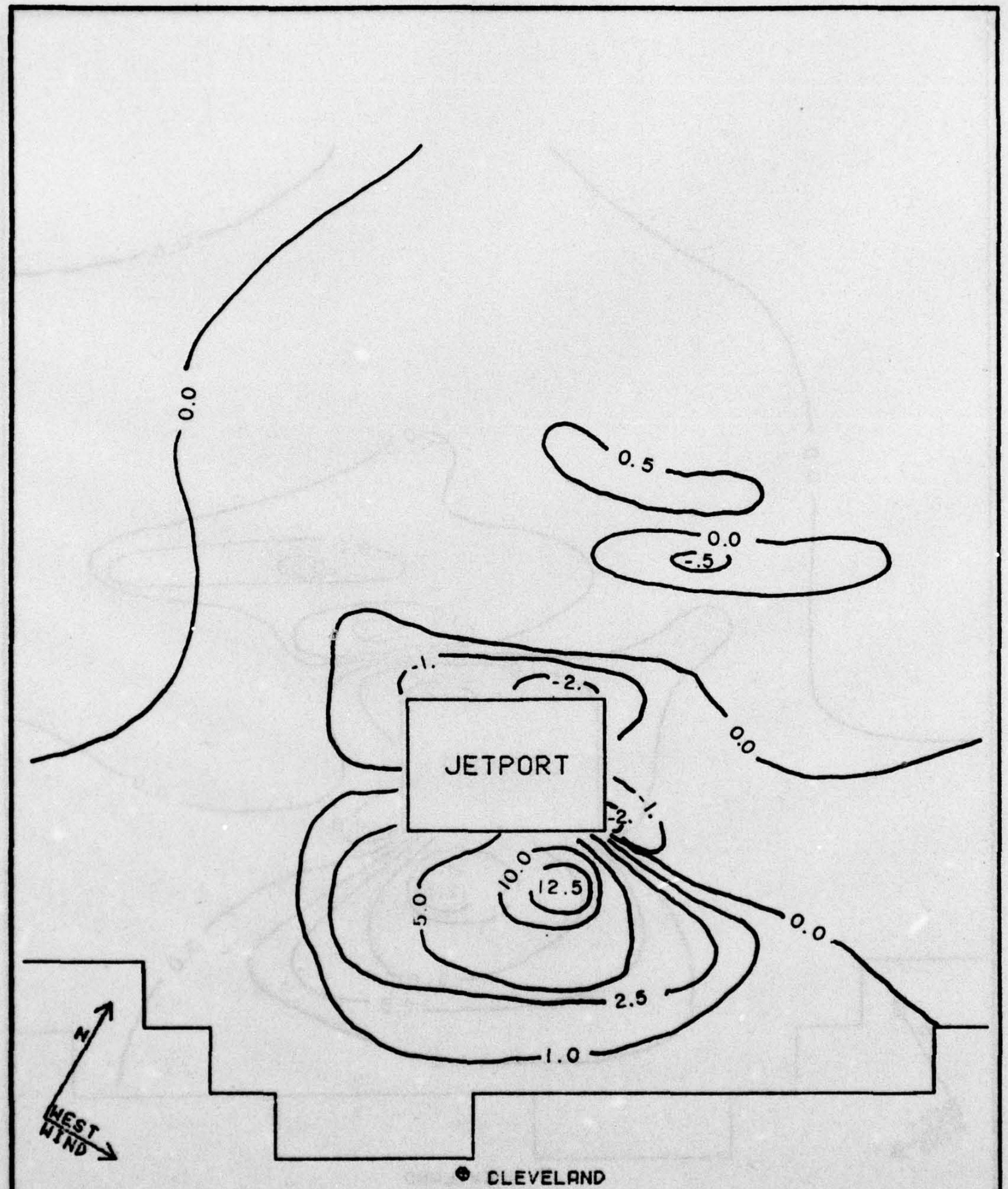


TEMPERATURE DIFFERENCE AT 0 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION

PLATE 49

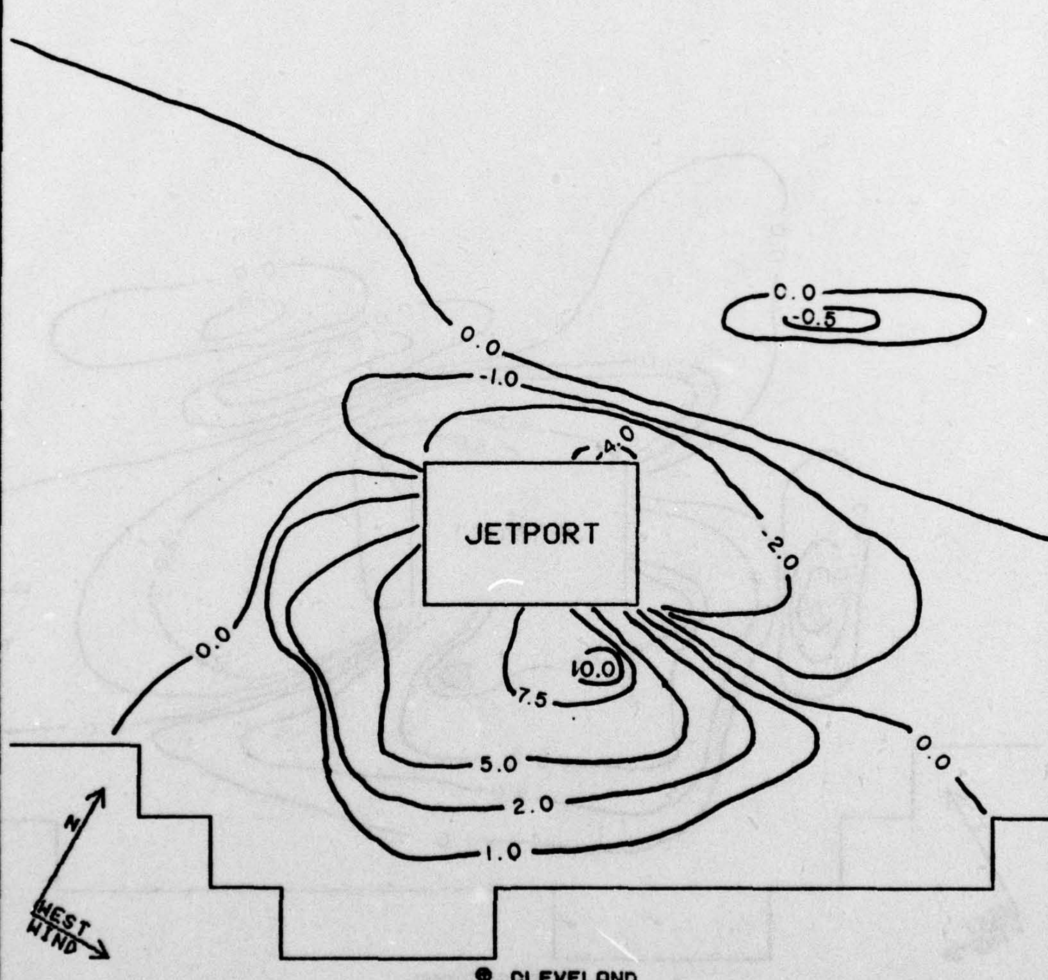


TEMPERATURE DIFFERENCE AT 10 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION

PLATE 50



TEMPERATURE DIFFERENCE AT 15 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION

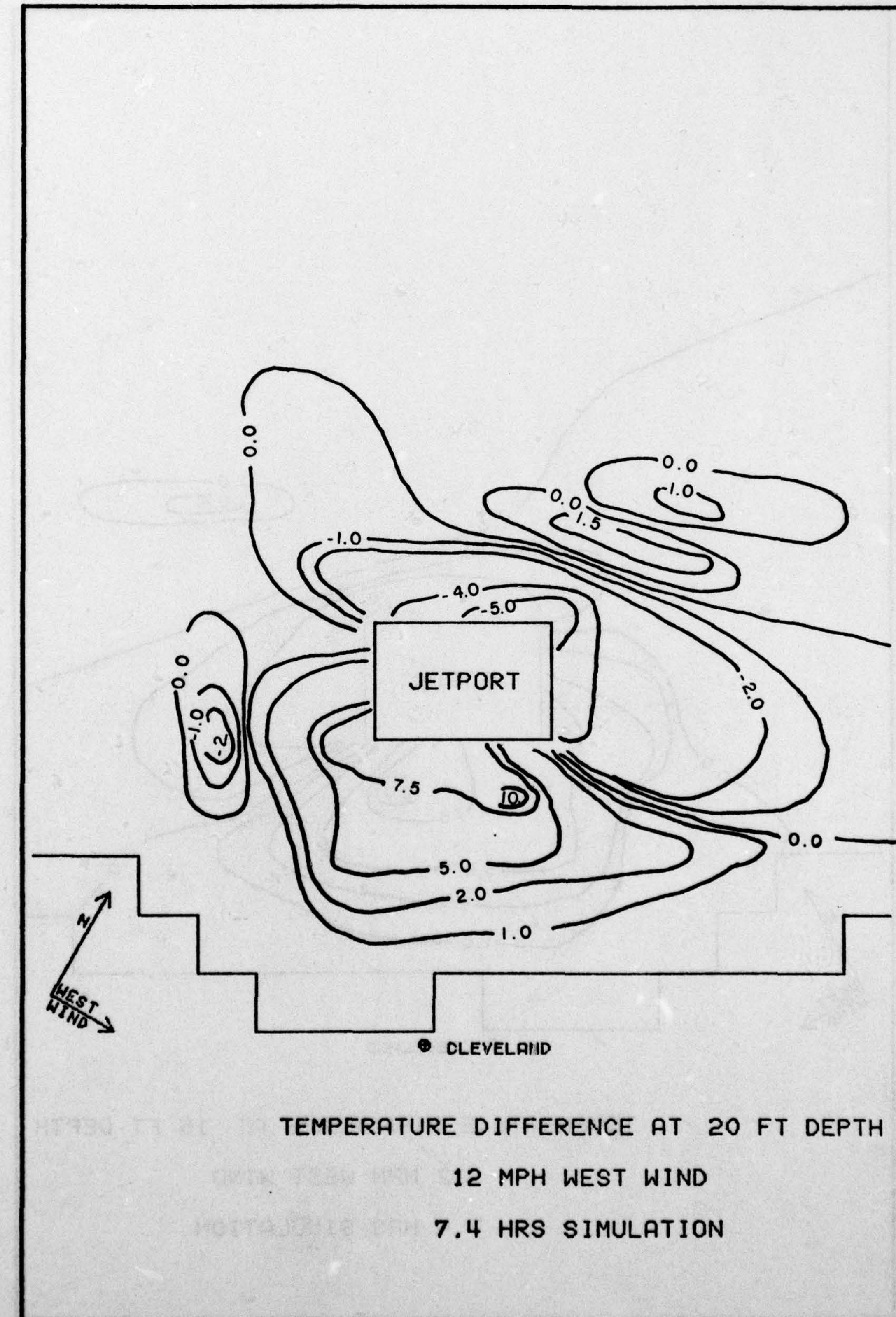
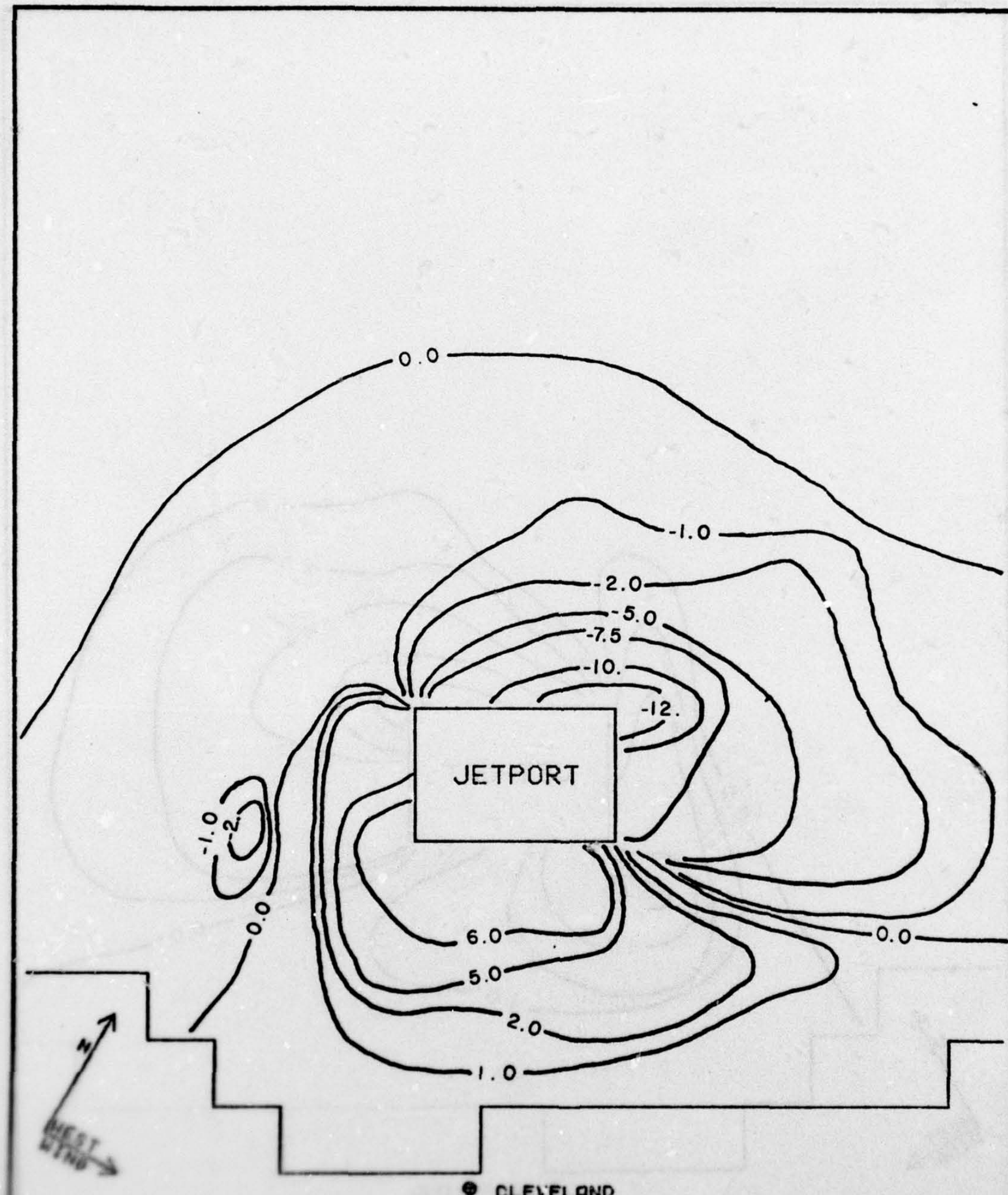

0.0
0.0
-1.0
0.0
1.5
-1.0
-4.0
-5.0
JETPORT
0.0
-1.0
-2
-2.0
7.5
10
0.0
5.0
2.0
1.0
N
WEST WIND
CLEVELAND
TEMPERATURE DIFFERENCE AT 20 FT DEPTH
12 MPH WEST WIND
7.4 HRS SIMULATION

PLATE 52

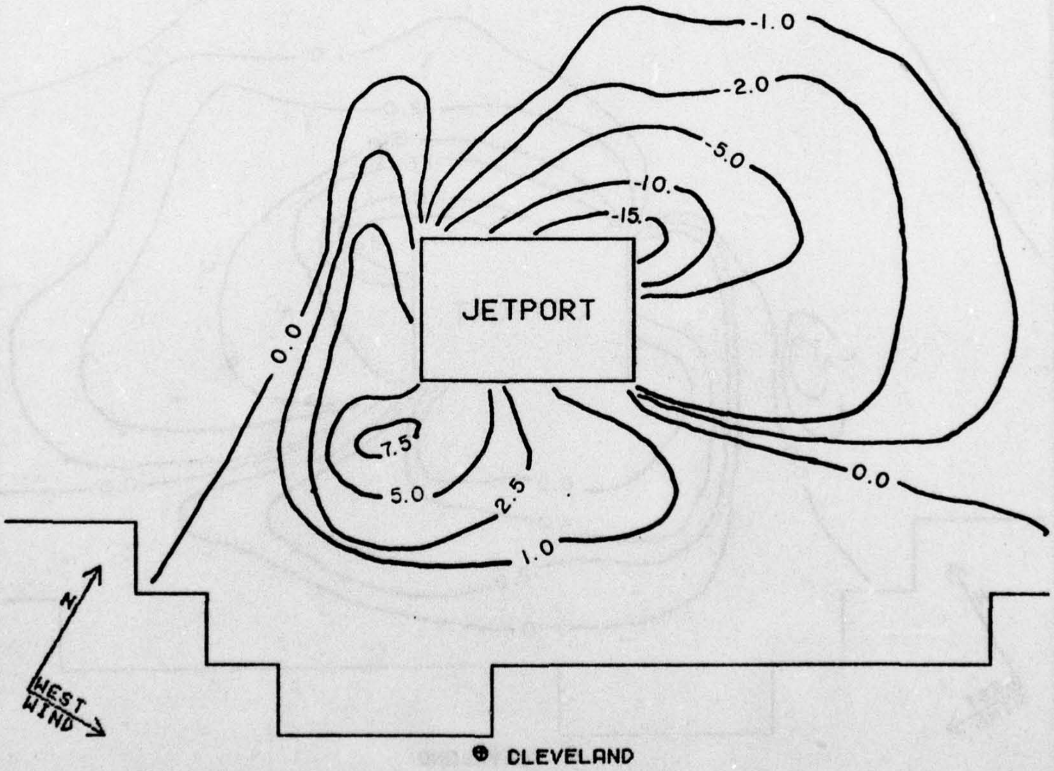


TEMPERATURE DIFFERENCE AT 30 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION

PLATE 53



TEMPERATURE DIFFERENCE AT 40 FT DEPTH

12 MPH WEST WIND

7.4 HRS SIMULATION

PLATE 54

APPENDIX A: NOTATION

A_H	Horizontal eddy viscosity
A_V	Vertical eddy viscosity
b_o	Horizontal reference length
B_H	Horizontal eddy diffusivity
B_V	Vertical eddy diffusivity
f_1	Outer boundary condition for u
f_2	Outer boundary condition for v
f_3	Outer boundary condition for ΔT
$f(\Delta T)$	Equation of state
Fr	Froude number
g	Gravitational acceleration
g_1	River outflow boundary condition for u
g_2	River outflow boundary condition for v
g_3	River outflow boundary condition for ΔT
h	Bottom depth
h_o	Reference depth
k	Dimensional Coriolis parameter
K	Surface heat transfer coefficient
P	Pressure
P_s	Surface pressure
Pr	Turbulent Prandtl number
Re	Reynolds number
Ro	Nondimensional Coriolis parameter
t	Time

twx	Surface wind stress in x direction
twy	Surface wind stress in y direction
T	Temperature
T_E	Equilibrium temperature
u	Velocity in x direction
u_o	Reference velocity
v	Velocity in y direction
w	Velocity in z direction
α	Constant in variable A_V term
β	Ratio of vertical to horizontal eddy diffusivities or constant in variable A_V term
γ	Ratio of vertical to horizontal eddy viscosities
ΔT	Temperature difference
$\Delta\rho$	Density difference
ρ	Density
ρ_o	Reference density
σ	Transformed vertical coordinate
Ω	Velocity in σ direction
$\overline{(\ )}$	Refers to dimensional quantity

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Durham, Donald L

Lake Erie International Jetport model feasibility investigation; Report 17-9: Results of numerical three-dimensional wind-driven circulation analysis for thermally stratified lake conditions / by Donald L. Durham, D. C. Raney. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1978.

26, 2 p., 54 leaves of plates : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; H-76-3, Report 17-9)

Prepared for Lake Erie Regional Transportation Authority, Cleveland, Ohio, under Task 17 of LERTA Third-Phase Airport Feasibility Study.

References: p. 25-26.

1. Airports. 2. Feasibility studies. 3. Lake currents. 4. Lake Erie. 5. Thermal stratification. 6. Wind waves. I. Raney, Donald C., joint author. II. Lake Erie Regional Transportation Authority. III. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper ; H-76-3, Report 17-9.

TA7.W34m no.H-76-3 Report 17-9